CHALMERS

Simulation of a heat/cold storage integrated with a non-residential building using ground pipes

Master of Science Thesis in Structural Engineering and Building Performance design

LISA OLAUSSON

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Department of Civil and Environmental Engineering
Division of Building Technology
Building Physics
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Chalmers Repro Service / Department of Civil and Environmental Engineering
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ABSTRACT

The demands on constructing high energy performance buildings are increasing on the building market. The demands are initiated by the Swedish government, partly due to more strict goals decided by the European Union, but also as a result from an increased interest of the energy and environmental work from users of the buildings.

Due to the increasing demands, technical solutions need to be used to improve and retrench the use of energy. The aim of this master thesis is to investigate one solution that may decrease the amount of energy that has to be bought. The solution is an underground energy storage mainly used over a 24-hour basis. The heat is stored during days and extracted during nights. The heating and cooling demand of the building is not lowered, but using an underground storage can decrease the amount of energy that has to be bought.

The main challenges in the thesis are to investigate both to what extent the heat storage can be used due to demands from the building as well as how the ground responds to the storing of thermal energy. The behaviour of a heat storage on 24-hour basis will be compared with a heat storage used on seasonal basis; the storage of heat from summer to winter.

A mathematical model is constructed and used when calculating the heating and cooling demand in the building and the behaviour of the heat and cold storage in the ground. The model contains three parts, the building, the pipe and the ground. The building part covers loads and behaviour of the interior of the building. The pipe part calculates the temperature distribution in the pipes, which are used to transport the energy from the building to the ground. In the ground part of the model, the temperature response in the ground is calculated. The parts are connected to each other and the behaviour of the system over time is calculated.

The result of the thesis shows that the building has a change of heating and cooling demand from night to day, which is the behaviour needed for the 24-hour storage, during spring and autumn. The period when the 24-basis storage can be used is therefore limited. The time of this period is sensitive to changes of requirements of indoor climate and variables in the building, as variation of size and duration of internal loads. The heat and cold storage on 24-hour basis uses less space in ground than storage on seasonal basis. That means that the pipes can be placed less deep and more close to each other. The functionality of the storage can also depend on the temperature on the ground surface. The 24-hour storage cannot save as much energy as the seasonal basis storage but it can help to lower the demand of energy from outside for heating and cooling during spring and autumn.

Key words: Pipe, heat and cold storage, energy storage, energy performance

Simulering av värme och kyllager integrerat med fastighet utnyttjande markförlagda slangar

Examensarbete inom Structural Engineering and Building Performance design
LISA OLAUSSON
Institutionen för bygg- och miljöteknik
Avdelningen för Byggnadsteknologi
Byggnadsfysik
Chalmers tekniska högskola

SAMMANFATTNING

Krav på att konstruera byggnader med hög energiprestanda ökar. Ökade krav kommer både från den svenska regeringen, med utgångspunkt från EU:s strängare regler, men även från fastighetsanvändarna, som ett resultat av deras ökande intresse för energi och miljöarbete.

På grund av ökande krav måste tekniska lösningar användas för att förbättra och minska energianvändningen. Målet med denna masteruppsats är att undersöka en lösning som kan minska den mängd energi som måste tillföras byggnaden. Lösningen är ett energilager i mark som främst ska lagra energin över en 24-timmars period. Värmen sparas under dagen och tas ut under natten. Värme- och kylbehovet i byggnaden minskar inte, men genom att använda ett termiskt marklager, kan mängden energi som måste köpas minskas.

De största utmaningarna är att undersöka både i vilken utsträckning värme och kyllagret kan användas med hänsyn till behov i byggnaden och med hänsyn till hur markens respons på termisk lagring. Användandet av ett värme- och kyllager på 24-timmar basis jämförs med att använda ett lager på säsongsbasis, då värme lagras från sommar till vinter.

En matematisk modell är konstruerad och denna används vid beräkning av värme och kylbehov i byggnaden och simulera responsen i marklagret. Modellen är uppdelad i tre delar kallade byggnaden, röret och marken. I byggnadsdelen beräknas laster och innetemperatur. I röret beräknas temperaturen av vätskan, som transporterar energin från byggnaden till marken. I markdelen beräknas temperaturresponsen runt röret. Delarna sammankopplas med varandra och hela systemet kan simuleras över tid.

Resultaten visar att under vår och höst har bygganden har en variation av kylbehov på dagen och värmebehov på natten, som är den sorts variation som behövs för lagring över en 24-timmars period. Tiden som 24-timmars lager kan användas är därför begränsad. Tiden på perioden är känslig för förändringar av innetemperaturkrav och för förändringar i byggnaden, så som variationer på längd och storlek på internlaster. Värme- och kyllagret som används på en 24-timmars basis använder mindre volym av marken än ett lager på säsongsbasis. Det betyder att rören kan placeras närmare ytan och närmare varandra för ett 24-timmars lager. Lagrets funktionalitet beror också på markens yttemperatur. För objektet i beräkningarna kan 24-timmar lagret inte spara lika mycket energi över året som säsongslagret, men det kan under vår och höst hjälpa till att sänka behovet av energi som måste tillföras bygganden.

Nyckelord: Rör, kyl och värmelager, energilager, energiprestanda

Contents

Preface

In this thesis the behaviour of heat and cold storage with ground pipes have been studied in interaction with the demand for climate control in a non-residential building. The work of the thesis started in middle of January in 2011 and has been finished in end of June the same year. The idea to the thesis was initiated by the company Axro Consult, which today is Sweco, and has been carried out together with the department of civil and environmental engineering on Chalmers University of Technology at the division of Building Technology.

The supervisor and the examiner at Chalmers has been Professor Carl-Eric Hagentoft who has helped with qualified support, information, systematic thinking and organization of the work. The supervisors, Johan Svensson and Ulf Aronson, who are employed at Sweco, have supported, giving input and comments during the process. Marek Bukowsky, employed at Sweco, has also supported the project by giving information about the function of climate systems but also by answering and asking questions.

Of big importance has also been the support from classmates, friends, family and other persons who were making the earth to a better place during the process of this master thesis.

Göteborg June 2011

Lisa Olausson

Notations

A	Area [m^2]
C	Heat capacity [J/K]
c	Specific heat capacity [Ws/(kgK)]
D	Distance to surface [m]
d	Diameter [m]
K	Thermal conductance [W/(mK)]
L_c	Characteristic length [m]
l	Length [m]
$\dot{m}$	Mass flow [kg/s]
Q	Energy [J]
q	Power of heat flow [W] or [W/m]
R	Thermal resistance [mK/W]
r	Radial distance [m]
T	Temperature [°C]
t	Time [s]
U_m	Overall heat transfer coefficient [W/m^{2}K]
V	Volume [m^3]
x	Distance [m]
η	Thermal efficiency [-]
λ	Thermal conductivity [W/mK]
μ	Dynamic viscosity [kg/(ms)] or [Ns/m^2]
v	Volume flow rate [m^3/s].
ρ	Density [kg/m^3]
COP	Coefficient of performance [-]
Nu	Nusselt number [-]
Pr	Prandtl number [-]
Re	Reynolds number [-]

1 Introduction

The demands on constructing high energy performance buildings are increasing on the building market. The demands are initiated by the Swedish government, partly due to more strict goals decided by the European Union, but also as a result from an increased interest from users of buildings. These users are for example companies or a business that wants to be in the front edge of the energy and environmental work

Due to the increasing demands technical solutions needs to be investigated to see how they can improve and retrench the use of energy. The aim of this master thesis is to investigate one solution that may be used to decrease the amount of energy that has to be bought. The solution is an underground energy storage with pipes that mainly is used over a 24-hour basis, the heat is stored during days when high internal loads heats the building, and extracted during nights when there is no activity in the building. The heating and cooling demand of the building is not lowered, but when the underground storage and the building is seen as a system, the bought energy or electricity can be decreased.

In the thesis the behavior of heat gains and heat losses in the building leading to a need of heating or cooling is investigated. The use of a 24-hour storage requires a building with a heating demand during night and a cooling demand during day. During what time of the year can a 24-hour storage be in use due to the requirement of a change between demand of cooling and heating over the days? The thermal energy needed for climate control is to be stored in the ground. To what extent this is possible and how big the storage needs to be is investigated. The size is discussed both with respect to energy and power. The underground storage with 24-hour basis is compared with using a underground storage on a 1-year basis.

The method used in this thesis is theoretical calculations in the computational program MATLAB. The system is modelled in three parts called the building, the ground and the pipe, which is used to transfer the heat from the building to the ground. To do the investigations, a certain building is used to be the object in the calculations. The building has activities and internal loads representing a hospital. The climate system in the house is only designed to the extent of using common temperatures for heating and cooling. That means that one presumption is that the system in the house is constructed to be able to release and collect the needed energy for heating or cooling. For the underground storage, the sum of the energy that is entering the ground and released from the ground should be zero. That mean, the question is to investigate storage of energy and the initial thermal energy in the ground should not be used as ha heat source. The underground storage is situated in ground made of clay.

The mathematical model makes it possible to simulate the behavior of the building and the ground and to reach the main goal with this thesis. The main goal is to investigate if it is possible to store the energy in ground made of clay and to estimate the part of the energy needed for climate control that can be covered by using the heat storage.

2 Theoretical background about energy use and common underground thermal energy systems

The requirement of the energy performance of buildings increases. The possible development of the energy requirements are described in Section 2.1. Due to need of higher energy performance technical solutions to lower the use of energy need to be made in the building. One solution is to use underground thermal energy. Underground thermal energy can be used just for heating or just for cooling or for cooling and heating over seasonal basis. Some common types of underground thermal energy outtake, called geothermal heat, or underground thermal energy storage are described in this Section 2.2.

2.1 Requirements of energy use today and in future

Today the requirements for energy consumption in buildings are regulated by a supplement to the building regulations, BBR, from Boverket, the Swedish national board of housing, building and planning. The regulation regulates the energy use in the building, which means the energy needed for heating, comfort cooling and heating of tap water. Energy needed for operating installations such as pumps, fans and technical equipment for controlling the system are also included as well as basic electricity for lightning. The supplement to BBR is valid since 2009. (Boverket 2009)

In Figure 2.1 the demands for non residential premises with other heating sources than electricity is shown, as well as the demands for properties with heating by electricity. The energy requirements valid today are shown in the first two bars. For buildings with high ventilation flow due to high hygiene demands an addition to the requirement can be made. The maximum additional energy use is shown by the lighter part of the bars in the Figure 2.1. (Boverket 2009)

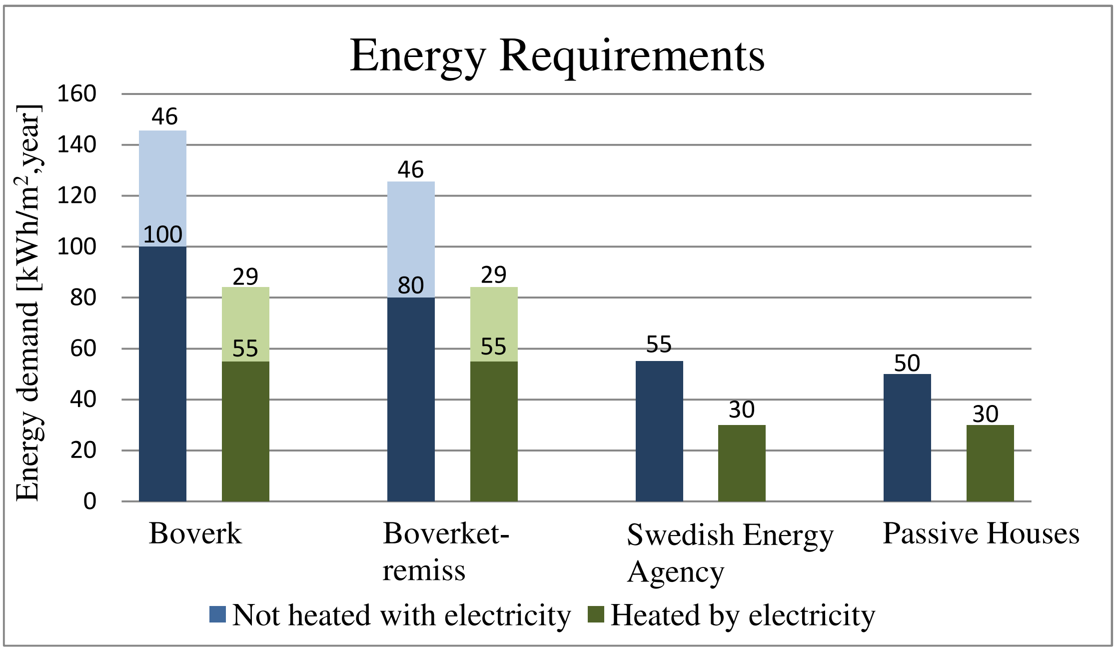


Figure 2.1 Different requirements on the energy consumption.

In October 2010 Boverket presented a proposal of a revision of their energy requirements from 2009. This revision is made to implement the EG-directive of the energy performance of buildings. At latest more strict demands should be in use in 2011 but at the moment the changes of BBR still are suggestions. The requirements of the energy performance presented in the proposal of the changes to BBR can be seen in the second groups of bars Figure 2.1. It can be seen that Boverket suggested the energy requirements to be stricter for buildings with another heating source than electricity. For buildings heated with electricity the demands should remain according to the supplement from 2009. (Boverket 2010)

The Swedish energy agency got a mission to develop a strategy which should increase the amount of low energy buildings in Sweden. The strategy developed to manage the energy goal that is the result from discussions in EU. In the discussions they used the definition "close to zero buildings", which means that the building has a very high energy performance and the small amount of energy used should come from renewable energy sources or from electricity or heat produced on site or close to the building. The result from the discussions from EU is formulated in a directive which says that all new buildings should be close to zero buildings in end of 2020. For dwellings owned by the public sector this goal should be reached even earlier, in the end of 2018. [Energimyndigheten 2010]

The limits of energy use decided by the Swedish Energy Agency can be seen in the third groups of bars in Figure 2.1. At the moment these limits presupposes a halving of lower limit of the today valid rules from Boverket, i.e. the supplement to BBR from 2009. The limits are presupposed on the requirements from Boverket due to the unconcerned definition of close to zero buildings. Thus this limit is in the level of what they expect a close to zero building to manage. The Swedish Energy Agency uses these values to give a signal about the future expected energy demands. The requirements from the Swedish energy agency are not rules but a goal levels for the energy consumptions. The rules for buildings are in the end decided by Boverket. (Energimyndigheten 2010)

There are today different types of low energy houses, which are close to the expected concept of NNE-buildings. A type with the clearest demand is called Passive House. To visualize the level of the energy consumption limit a close to zero building could have in the future, also the demands of Passive Houses are shown in Figure 2.1. It should be noticed that these level is for valid for residences and schools and not for non-residence houses. The level is a simplification of a demand that could be used for both types of buildings. The more generalized requirement is not so clear specified and depends on a weighting of the type of energy bought. (Forum för Energieffektiva byggnader 2009)

The strategy the Swedish energy agency developed should, due to the mission from the Swedish government, be made in accordance with Boverket and other involved participants on the building market. Despite that the strategy should be developed in cooperation with Boverket the publication of this strategy presents much stricter requirements on the energy consumption than the proposal to BBR made by Boverket. The Swedish Energy agency says that their more ambitious requirements of the energy use are needed to manage the directive from EU with 100% close to zero buildings in end of 2020. (Energimyndigheten 2010) Boverket instead motivates their new requirements with that they are close to the limit of how hard the demands of the energy performance can be and still get profitableness on the properties over a 40-

years calculation period. A higher demand could be more expensive and therefore inhibit the development of constructing new buildings. (Boverket 2010)

2.2 Different systems for underground thermal energy

Thermal energy systems could either be constructed to use the geothermal heat from the ground or from water or for storing energy that can be used later. There are different systems to extract heat from ground which are shown in Figure 2.2 and Figure 2.3. All the systems uses the ground temperature, which is said to be quite constant. A heat pump is used to lift this temperature in the ground to a higher temperature. This is the temperature which can be used for heating for example a building. (Lund, Sanner, Rybach, Curtis, Hellström 2004)

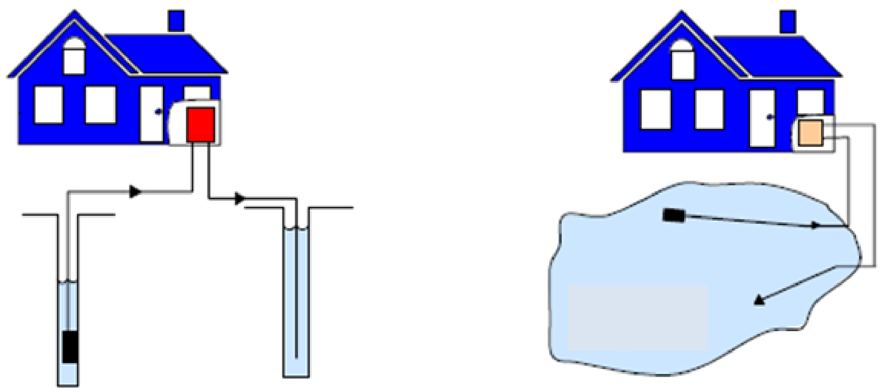


Figure 2.2 Open loops systems (Lund, Sanner, Rybach, Curtis, Hellström 2004)

Figure 2.2 shows open loop systems. In these systems the water is taken into the heat exchanger and the return water, which has released energy to the house, is let out in another place nearby. (Lund, Sanner, Rybach, Curtis, Hellström 2004) The system, also called Aquifer thermal energy storage, can also be used for seasonal cooling and heating respectively, this is due to that the system will get a warm and a cool side. In summer, the water is heated in the building, due to cooling of the indoor air, and this water is then pumped back to the warm side of the aquifer. This side can get a temperature at usually about 12-15 degrees. In winter, while the building is heated, the flow in the system is reversed and the temperature at the cool side can be 4-7 degrees. (Lundström 2009)

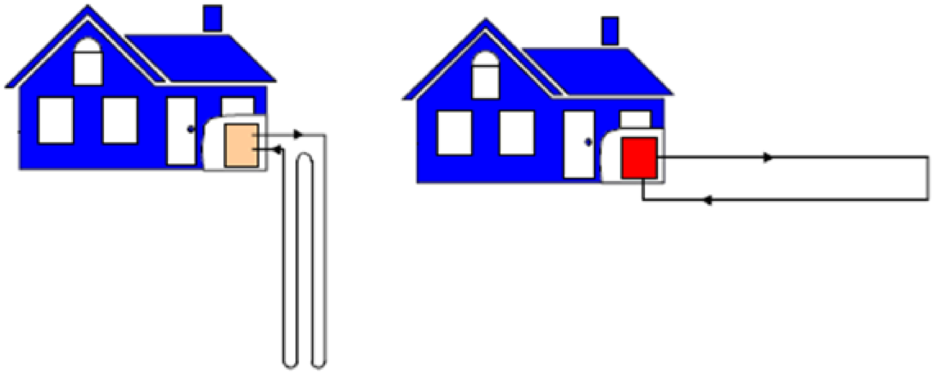


Figure 2.3 Closed loops systems. (Lund, Sanner, Rybach, Curtis, Hellström 2004)

In the systems shown in Figure 2.3 a closed loop is used. Using heat energy from the ground is called geothermal heat. The system could either be placed vertically or horizontally in the ground to collect heat, this is called geothermal heat. The vertically placed loop uses a borehole to place the pipes. (Lund, Sanner, Rybach, Curtis, Hellström 2004) These holes are usually connected with rock were the heat can be extracted. After a time the extraction of heat from the rock gets slower. The gradually reduction of the capacity of the bore hole depend, among other reasons, on the conductivity of the ground. If the conductivity is too low, the heat cannot be transferred to the pipe fast enough, the temperature at the borehole will be too low to heat the fluid in the pipe. The system can also be used as storage, to use heat from the ground in winter and release heat to the ground in summer. (SGU)

For the horizontal placed loop, about 1-2 meter deep in ground, the temperature in ground falls during winter when the building is heated. How fast and how much the temperature falls is dependent on the heat capacity of the ground as well as on the conductivity of the ground. During summer season the sun is hitting the ground surface and the temperature around the pipe rises. (Heat Pump Centre)

In Europe most of the thermal energy sources is used only in heating mode. But due to an increase of internal heat in the building, also cooling is needed. Therefore it will be of more importance to use the ground for both cooling and heating. (Lund, Sanner, Rybach, Curtis, Hellström 2004) some commercial buildings use the bore hole in rock for cooling and heating on seasonal basis. (Heat Pump Centre) In larger boreholes systems it is of interest to know the balance of extracted heat and return heat to insure a proper long term use of the bore hole. If no balance, it may be necessary to charge the borehole with for example heat during summer. (Lund, Sanner, Rybach, Curtis, Hellström 2004)

Which type of system that can be used is dependent on the geothermal condition but the choice of system is also due to the type of building. The building and its activities decides the volume of energies and power that is required from the storage system. Of course the profitability of the system compared with other type of systems is of importance. (Lundström 2009)

3 Reasons to the choice and description of the system used in the calculations

The requirements of the energy consumption of the building will be stricter. The thickness and the performance of the building envelope have been increased but to improve the energy performance of the building, technical solutions need to be made. One solution is to use thermal energy heating. But for many buildings also comfort cooling is needed. In this thesis, the ground should be used for both cooling and heating. Many buildings use the underground thermal energy storage for heating and cooling on seasonal basis. For commercial buildings there are often only activities during daytime, which causes internal heat. The hypothesis is that underground thermal energy storage also can be used for storage under a shorter period of time, when a building is cooled during days and heated during nights. This requires certain conditions of the ground, the building and the activities in the building. An exact description of the system and material data used in the calculation can be seen in Appendix I. The Sections 3.1 and 3.2 gives a general description of the conditions of the ground, the building and the parts of the system. Also motivations to the choice of system the mathematical model is based on, which is described in Chapter 4, are presented.

3.1 Description of the building

The hypothesis is that a building with high performance together with the internal loads could give a heat surplus in the building during daytime, and a heat deficit during nights for most of the year. That means a heat surplus during daytime even during the colder season.

The heat gains and heat loss in the building depend on the outside temperature, sun, activities in the building and transmission losses. The system that handles the heat surplus and heat deficit in the building is designed so it can handle the claimed power. The climate system in the building is therefore not a limiting part for satisfying the demands for climate control. There are some demands on temperatures in the system. For example there are demands on the cooling system that force it to work between two common temperatures for cooling systems. The limits are described more detailed in when describing the mathematical model in Chapter 3.

3.2 Description of the storage

The system should not using any other heat source than the energy from the building. That means the balance of extracted and returned energy has to be ensured in order to keep the effectiveness of the storage. The heat storage will be placed horizontally in the ground consisting of clay. Clay has certain material data that decides the spread of the energy in the ground and how fast the energy can energy can enter the ground. The surface temperature will also influence the calculations.

4 Description of the mathematical method

The mathematical model describes the system of underground energy storage and the interaction with the building. To construct the mathematical model the system is divided into three sub parts, called the building, the pipe and the ground, which are illustrated in Figure 4.1. A theoretical model is developed for each sub part individually and described in the following sections. The parts interacts with each other over time, this is described in Section 4.4. The code for the mathematical model is written in the computing program MATLAB (MathWorks 2010) and can be seen in Appendix II.

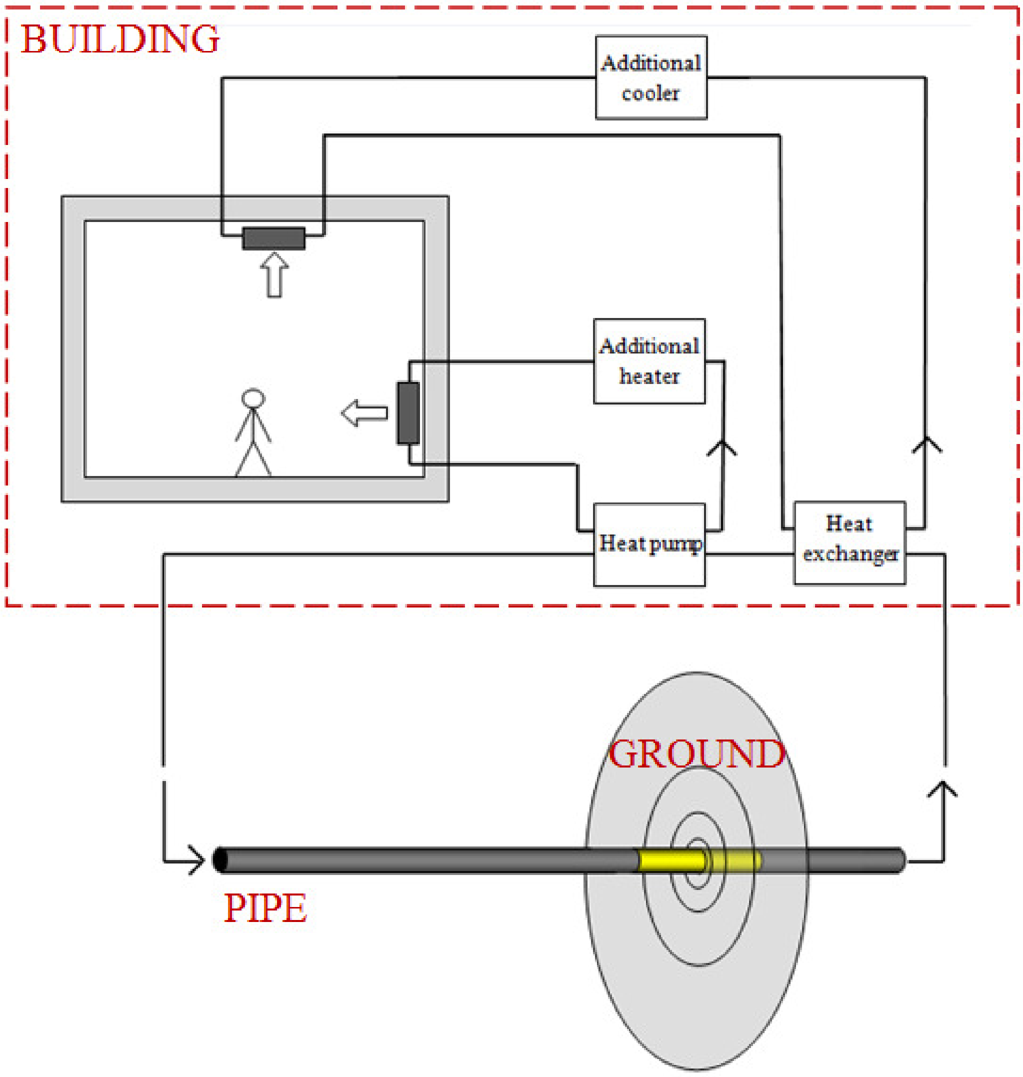


Figure 4.1 The three subsystems, the building, the pipe and the ground, used in the calculations.

4.1 Model of the building

The building is seen as a box with heat gains and heat losses which affects the indoor temperature. Since the building is modelled in one piece there is no respect taken to different heat gains in different rooms. The heat gains and losses which are considered in the model is illustrated in the Figure 4.2. Further, the calculations of the power for each load are defined.

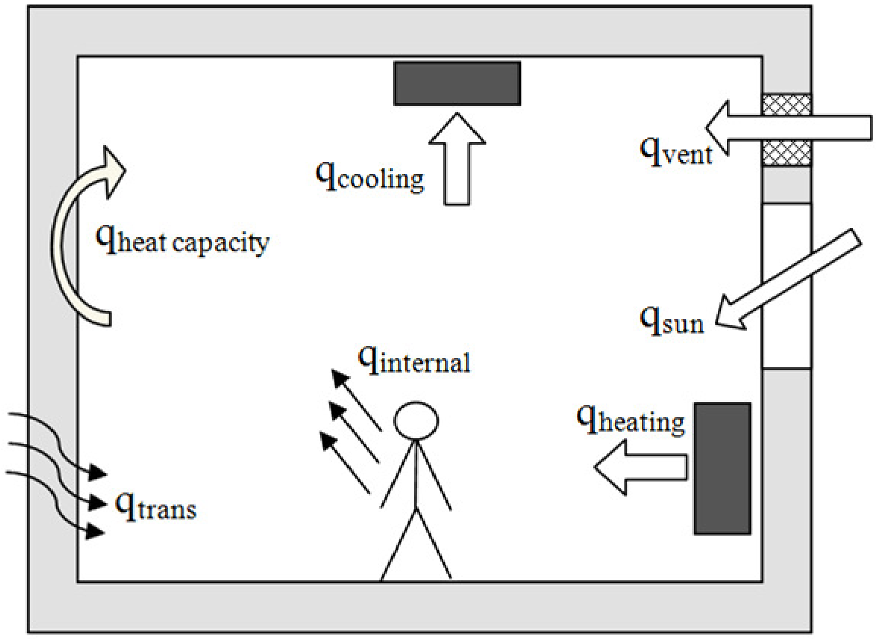


Figure 4.2 Illustration of the model of the building with its loads.

4.1.1 Internal heat production

Internal heat, $q_{internal}$ (W), is due to the production of heat in the house. The internal heat production is dependent on the activity in the building and varies with time.

4.1.2 Insolation

The heat gains due to sun, q_{sun} (W), depend on the location, geometry and the placement of the windows of the building.

4.1.3 Transmission

The flow of energy, q_{trans} (W), transmitted through the walls is calculated with equation (4.1).

$$q_{trans} = U_m A_{around}(T_{out} - T_{indoor}) \quad [\mathrm{W}] \tag{4.1}$$

U_m [W/m^{2}K] is the overall heat transfer coefficient for the whole building and A_{around} is the area of all the surfaces enclosing the indoor climate. T_{out} is the outdoor temperature, which is dependent on the site the building is located on. The T_{indoor} is the temperature in the building.

4.1.4 Ventilation

To calculate the heat gain or heat loss due to the ventilation, q_{vent}, the ventilation system needs to be described. In the system a heat exchanger is used, which is in use while the outside temperature is under a requirement of a lower demand of the inlet air temperature. The heat exchanging does only heat the incoming air, which means no cooling by the heat exchanger for high outdoor temperatures. The principal scheme of the heat exchanger can be seen in Figure 4.3.

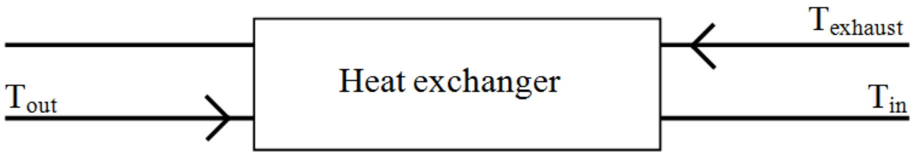


Figure 4.3 Principal scheme for the heat exchange of the ventilation air

The cooling or heating power, q_{vent} [W], transported with the ventilation air is calculated with equation (4.2).

$$q_{vent} = \dot{m}_{air} c_{air} (T_{in} - T_{indoor}) \text{ [W]} \tag{4.2}$$

c_{air} [Ws/kgK] is the heat capacity of air and $\dot{m}_{air}$ (kg/s) is the mass flow of air. Equation (4.3) is used to calculate $\dot{m}$.

$$\dot{m}_{air} = \dot{v} \rho_{air} A_{floor} \text{ [kg/s]} \tag{4.3}$$

$\dot{v}$ [m^3/sm^2] is volume of ventilation per square meter floor area and time. ρ_{fluid} [kg/m^3] is the density of the air and A_{floor} is the floor area of the ventilated spaces.

For outdoor temperatures higher than the minimum demand of inlet temperature, the inlet temperature, T_{in}, is equal to the outdoor temperature. For equal mass flow in and out in the heat exchanger the temperature after the heat exchanger, T_{in}, is calculated with equation (4.4).

$$T_{in} = T_{indoor} + (1 - \eta)(T_{outdoor} - T_{indoor}) \text{ [°C]} \tag{4.4}$$

η is the thermal efficiency of the heat exchanger.

4.1.5 Heating system

To heat up the building a heat pump and an additional heater is used, this can be seen in Figure 4.4. A part of the heating demand in the building is extracted from the ground with a heat pump. If not the heat extracted from the ground can fulfil the demanded heating need an additional heater is used. The system in the building should be designed so Q_{demand} [J] can be released to the indoor air, i.e., $q_{heating}$ [W] in the Figure 4.4 can always manage to release Q_{demand} [J] over the time step.

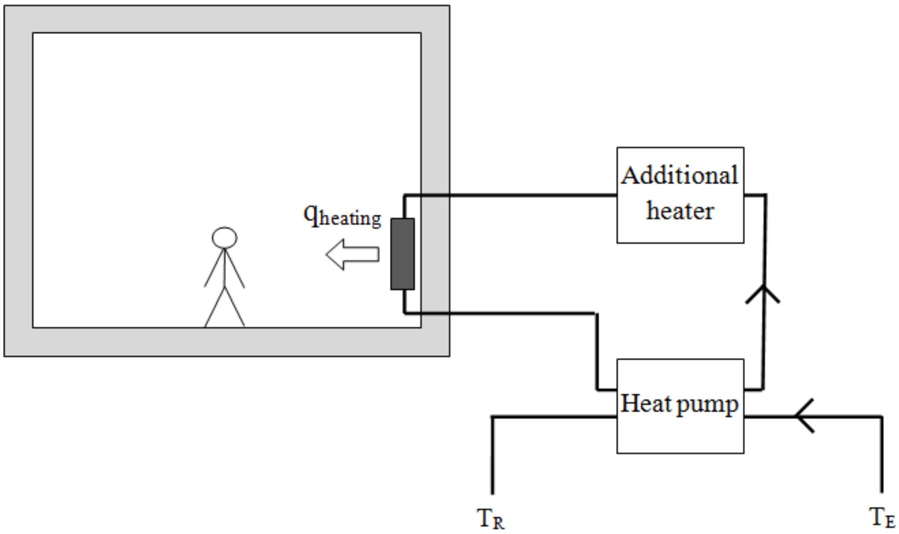


Figure 4.4 Principal sketch of the heating system.

The energy needed for heating is specified by calculating a need of temperature change in the building. For creating the temperature change the energy, Q_{demand}, is needed for each time step. The heat pump can extract heat from the fluid in the pipe as long as the return temperature is above 0°C, this is illustrated in Figure 4.5. The temperature limit is due to avoid freezing of the ground around the pipe. If Q_{demand} can be extracted completely from the fluid which is heated in the ground depend on the entering temperature, T_E, to the heat pump as well as the volume flow of water, i.e. of the heat capacity of the water passing the heat pump over the time step.

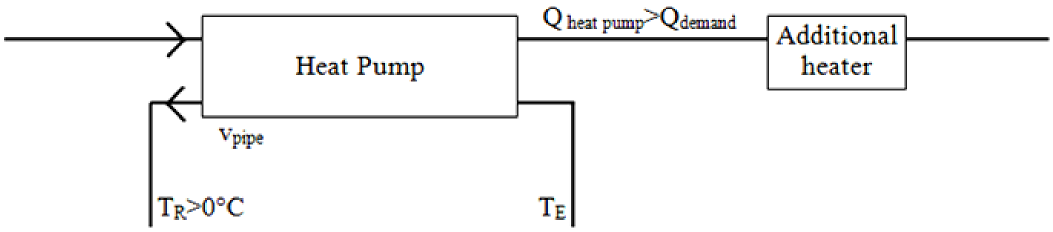


Figure 4.5 Principal scheme for the heat pump and additional heater.

If the heat fluid from the ground and the return temperature demand do not allow the heat pump to produce the demanded energy, an additional heater will be used that adds the remaining power to the heat carrier in the building.

The heat pump uses both electricity and heat from the ground to produce the energy demand. The given power from the heat pump can be calculated with equation (4.5).

$$q_{heat\ pump} = q_{ground} + q_{electric} \quad \text{[W]} \tag{4.5}$$

The electricity that needs to be added to the heat pump depends on the coefficient of performance. The coefficient of performance is a relationship of electricity provided to the heat pump and heat produced by the pump. COP is calculated with equation (4.6).

$$COP = \frac{Q}{W} \quad \text{[-]} \tag{4.6}$$

Where W [J] is the work provided to the process, i.e. the electrical part, and Q [J] is produced heat. If COP=4 the system uses 1 part electricity and 3 parts heat to produce the final heat energy. For steady state the same equation is valid with respect to power instead of energy. That means equation (4.7) can be used.

$$COP = \frac{q_{heat\,pump}}{q_{electric}} \text{ [-]} \tag{4.7}$$

The coefficient of performance does vary with the temperature lift but COP will be used as a constant in the calculations. An ideal coefficient of performance, called Carnot coefficient of performance, COP_c, for heating can be calculated with equation (4.8).

$$COP_c = \frac{T_1}{T1 - T_2} \text{ [-]} \tag{4.8}$$

Where T_1 [K] is the high temperature level and T_2[K] is the low temperature level. For practical use COP can be estimated to about 50% of COP_c. (Lindholm, T. 2009)

It is only the energy taken from the fluid in the pipe that affects the return temperature, T_R, of the fluid. It is then necessary to calculate the electrical part of the heat produced in the heat pump. Equation (4.9) is used to calculate the electrical part of the produced heat.

$$q_{electric} = q_{heat\,pump}/\mathrm{COP} \text{ [W]} \tag{4.9}$$

The temperature change of the fluid is due to the outtake of power from the fluid, which is the difference between $Q_{heat\,pump}$ and the added electricity $Q_{electric}$. That means the return temperature of the fluid can be calculated with equation (4.10).

$$T_R = T_E + (q_{heat\,pump} - q_{electric})/(\dot{m}_{fluid} * c_{fluid}) \text{ [°C]} \tag{4.10}$$

Where c_{fluid} [Ws/kgK] is the specific heat capacity of the fluid and $\dot{m}_{fluid}$ [kg/s] is calculated with equation (4.11).

$$\dot{m}_{fluid} = \dot{v}\rho_{fluid} \text{ [kg/s]} \tag{4.11}$$

Where $\dot{v}$ [m^3/s] is the volume flow rate.

If the temperature of the entering fluid is too low, only a part of the needed heat energy can be taken from the ground. The rest has to be taken with the additional heater. The power that can be taken from the ground until the return temperature reaches the limit of 0°C is calculated with equation (4.12).

$$q_{ground} = (T_E - 0)/(\dot{m}_{fluid} * c_{fluid}) \text{ [W]} \tag{4.12}$$

According to equation (4.5) the electrical part can be added to Q_{ground} to calculate the total power from the heat pump. If this total power is less than the demanded power the additional heater is needed. The power needed from the additional heater is calculated with equation (4.13).

$$q_{heater\,additional} = q_{demand} - q_{heat\,pump} \text{ [W]} \tag{4.13}$$

The total power from heat pump is the sum of the power taken from the ground, q_{ground}, and the electrical part used in the heat pump, that is equation (4.5). In the equations (4.14- 4.17) the equation (4.5) is derived to give equation (4.18). This equation can calculate the total power from the heat pump by only using COP and the energy extracted from the ground.

$$COP = \frac{q_{heat\ pump}}{q_{electric}} = \frac{q_{ground}}{q_{electric}} + \frac{q_{electric}}{q_{electric}} \quad [-] \tag{4.14}$$

$$COP = \frac{q_{ground}}{q_{electric}} + 1 \quad [-] \tag{4.15}$$

$$q_{ground} = q_{electric}(COP - 1) \quad [W] \tag{4.16}$$

Using equation (4.7)

$$q_{ground} = q_{heat\ pump}(COP - 1)/COP \quad [W] \tag{4.17}$$

And the total heat pump power can be calculated with equation

$$q_{heat\ pump} = q_{ground} * COP/(COP - 1) \quad [W] \tag{4.18}$$

4.1.6 Cooling system

The cooling system in the house is designed to satisfy the cooling demand in each time step. The cooling of the fluid to the cooling system is principally made with a heat exchanger and an additional cooler. This is shown in Figure 4.6.

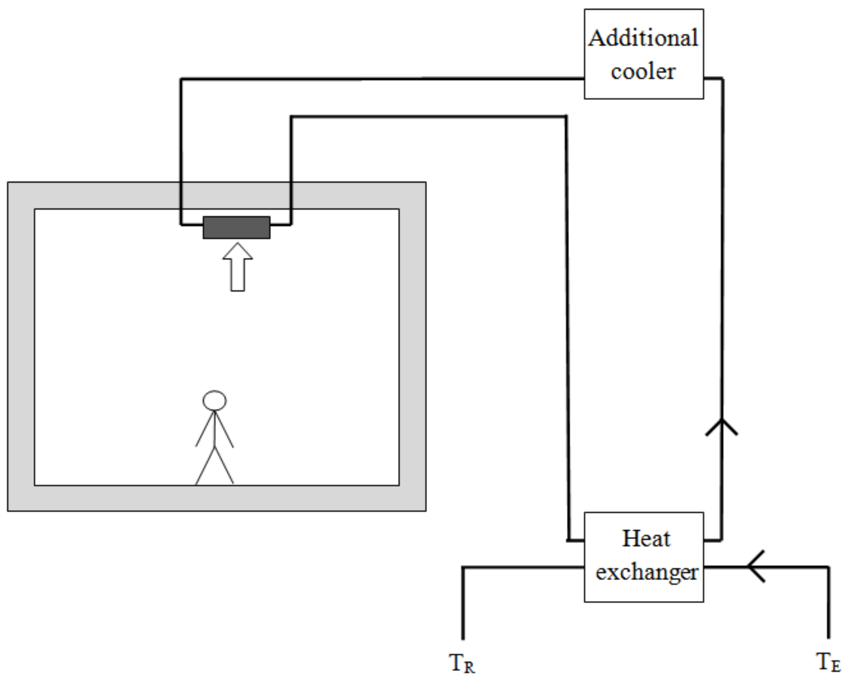


Figure 4.6 Principal sketch of the cooling system

The heat exchanger is said to be ideal, i.e. all the energy leaving the fluid in the circuit of the cooling units is entering the fluid in the pipes to the ground. That means the efficiency of the heat exchanger is 100%. But to have realistic temperatures in the systems a temperature drop between the inlet on the cooling unit side and the outlet on the pipe leading to the ground side is used in the calculations. I.e. there is a temperature drop between $T_{R-cooling\ unit}$ and T_R. The size of the temperature drop is due to the choice of heat exchanger. A principal scheme of the heat exchanger used for cooling can be seen in Figure 4.7.

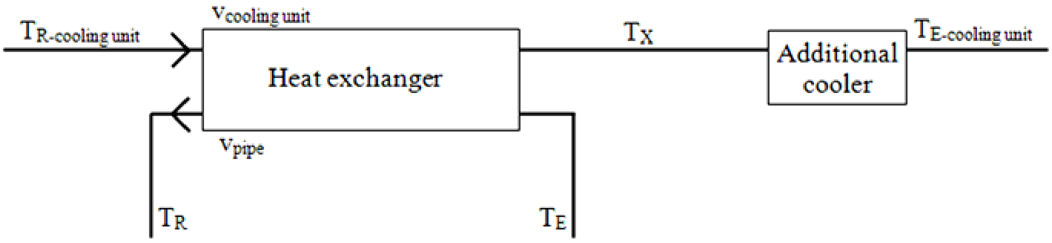


Figure 4.7 Principal scheme for the heat exchanger and additional cooler

In the system the entering temperature, $T_{E-cooling\ unit}$, and the return temperature, $T_{R-cooling\ unit}$, of the cooling unit is constant, while the flow, $v_{cooling\ unit}$, in the cooling unit varies due to the cooling demand. To collect the amount of energy that should leave the building the flow of the fluid in the cooling unit system, $v_{cooling\ unit}$, varies. The flow depends on the cooling demand, if the cooling demand increases the flow rate increases. The flow rate is calculated with equation (4.19).

$$v_{cooling\ unit} = \frac{-q_{demand}}{\rho_{fluid} c_{fluid} (T_{R-cooling\ unit} - T_{E-cooling\ unit})} \text{ [m}^3\text{/s].} \qquad (4.19)$$

This flow rate is used to calculate the temperature change of the fluid in the ground pipe system, were there is another fluid flow rate, v_{pipe} [m^3/s]. The return temperature of the fluid in the pipe system is calculated with equation (4.20).

$$T_R = T_E + \frac{v_{cooling\ unit}}{v_{pipe}} (T_{R-cooling\ unit} - T_{E-coolin\ unit}) \text{ [°C]} \qquad (4.\ 20)$$

If the return temperature is lower than the return temperature from the cooling unit, $T_{R-cooling\ unit}$ minus the temperature drop, T_{drop}, all the energy collected from the indoor air enter the fluid in the pipe. I.e., the additional cooler does not need to be used if equation (4. 21) is satisfied.

$$T_R \leq T_{R-cooling\ unit} - T_{drop} \text{ [°C]} \qquad (4.21)$$

If the statement is not fulfilled the additional cooler need to be used. The part of the cooling demand that has to be covered by the additional cooler can be calculated. This is made by calculating the temperature in between the heat exchanger and the additional cooler, that is the temperature T_x in Figure 4.7. To do this the return temperature, T_R in the pipe needs to be known. When equation (4.21) is not fulfilled T_R is calculated by equation (4.22).

$$T_R = T_{R-cooling\ unit} - T_{drop} \text{ [°C]} \qquad (4.22)$$

The temperature T_x is calculated by equation (4.23). The equation is valid for the same fluid in the cooling unit as in the pipe; it is only the volume flow rate that differs.

$$T_x = T_{R-cooling\ unit} - \frac{v_{pipe}}{v_{cooling\ unit}} * (T_R - T_E) \text{ [°C]} \qquad (4.23)$$

When T_x is known the extra power needed to get the demanded entering temperature to the cooling system, $T_{E-coolin\ unit}$, is calculated by equation (4.24).

$$q_{additional\ cooler} = \rho_{fluid} c_{fluid} v_{cooling\ unit} (T_x - T_{R-cooling\ unit}) \text{ [W]} \qquad (4.24)$$

4.1.7 Change of indoor temperature

The indoor temperature is calculated with an energy balance equation, equation (4.25). An illustration of the equation can be seen in Figure 4.8. The balance equation means that the change of energy in the building is equal to the heat gain or loss of energy due to internal heat production, sun, ventilation, transmission and energy transport through the climate system.

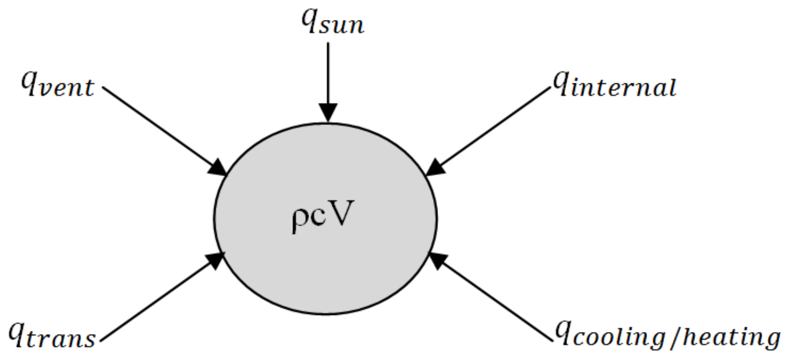


Figure 4.8. An illustration of the balance equation. The different heat gains or losses affects the building which is seen as the circle with the heat capacity ρcV.The amount of the heat capacity in the circle and how much energy that comes into the circle during a time step causes a temperature change of the material in the circle.

$$\sum(C)\frac{dT_{indoor}}{dt} = q_{vent}(t) + q_{sun}(t) + q_{trans}(t) + q_{internal}(t) + q_{cooling/heating}(t)$$
[W]

(4.25)

$\sum(C)$ [J/K] is the total heat capacity of the materials which can active in the process of changing temperature in the building. This means the heat capacity of the air as well as the heat capacity of walls, furniture's etc. The exchange of energy due to heat capacity in the building is illustrated with the bended arrow in Figure 4.2, called $q_{heat\ capacity}$. The heat capacity is calculated with equation (4.26). (Hagentoft, C.-E. 2001)

$$C = \rho cV \text{ [J/K]} \tag{4.26}$$

Where ρ [kg/m^3] is the density of the material, c [Ws/(kgK)] is the specific heat capacity and V [m^3] is the volume of the material. It is the surface layer of the materials that react with the indoor temperature instantly, the deeper material has a delayed reaction due to properties of thermal conductivity in the material. To say that all the volume of the material react with the change of energy in the building a simplification used. It is also hard estimate the volume of the material that is involved in the process of changing thermal energy. Due to this source of error, a finer model for the heat exchange with the heat capacity in the building is not increasing the accuracy of calculations.

4.2 Model of the pipe

The pipe is in the mathematical model divided into segments. An illustration of this can be seen in Figure 4.9. Each segment has a transverse heat flow to a, for each segment and each time step, constant ambient temperature. The transverse heat flow depends on the flow rate of the fluid in the pipe, the resistance to the ambient temperature and temperature potential between the fluid and ambient ground. The temperature potential is in this model caused by the ambient temperature and the incoming temperature to the segment, T_{seg}. The transverse heat flow causes a change in temperature of the fluid, ΔT. This change in temperature decides the inlet temperature to the next segment, T_{seg+1}.

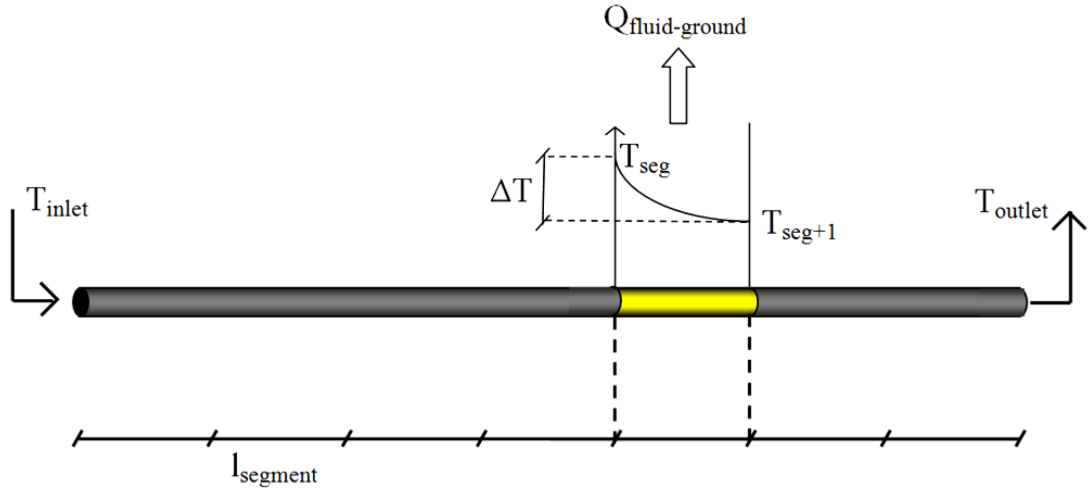


Figure 4.9 An illustration of how the pipe is divided into segment and how the temperature drop, ΔT, in the segments causes a transverse heat loss to the ambient ground.

The outlet fluid temperature for each segment is calculated with equation (4.27).

$$T_{seg+1} = T_{seg} + \left(T_{amb,seg} - T_{seg}\right)\mathrm{e}^{-\frac{l_{seg}}{L_c}} \tag{4.27}$$

L_c is the characteristic length and a measure of the dispersion between the convective heat transfer in the pipe and the transverse conductive heat transfer. The characteristic length for one segment of the pipe is calculated with equation (4.28).

$$L_c = R_{pipe-i} v_{fluid} c_{fluid} \rho_{fluid} = \frac{1}{K_{fluid-1}} v_{fluid} c_{fluid} \rho_{fluid} \quad [\mathrm{m}] \tag{4.28}$$

v_{fluid} is the volume flow rate, c_{fluid} and ρ_{fluid} is the heat capacity and the density of the fluid respectively. R_{pipe-i} is the resistance between the pipe and the node in the first circular element in ground. (Karlsson, H. 2010). This resistance is calculated by taking one over the conductance, $K_{fluid-1}$, in equation (4.30).

4.3 Model of the ground

The temperature distribution in the ground is calculated for each time step. To calculate the temperature distribution, circular elements is created in radial direction around each segment of the pipe; this is illustrated in Figure 4.9.

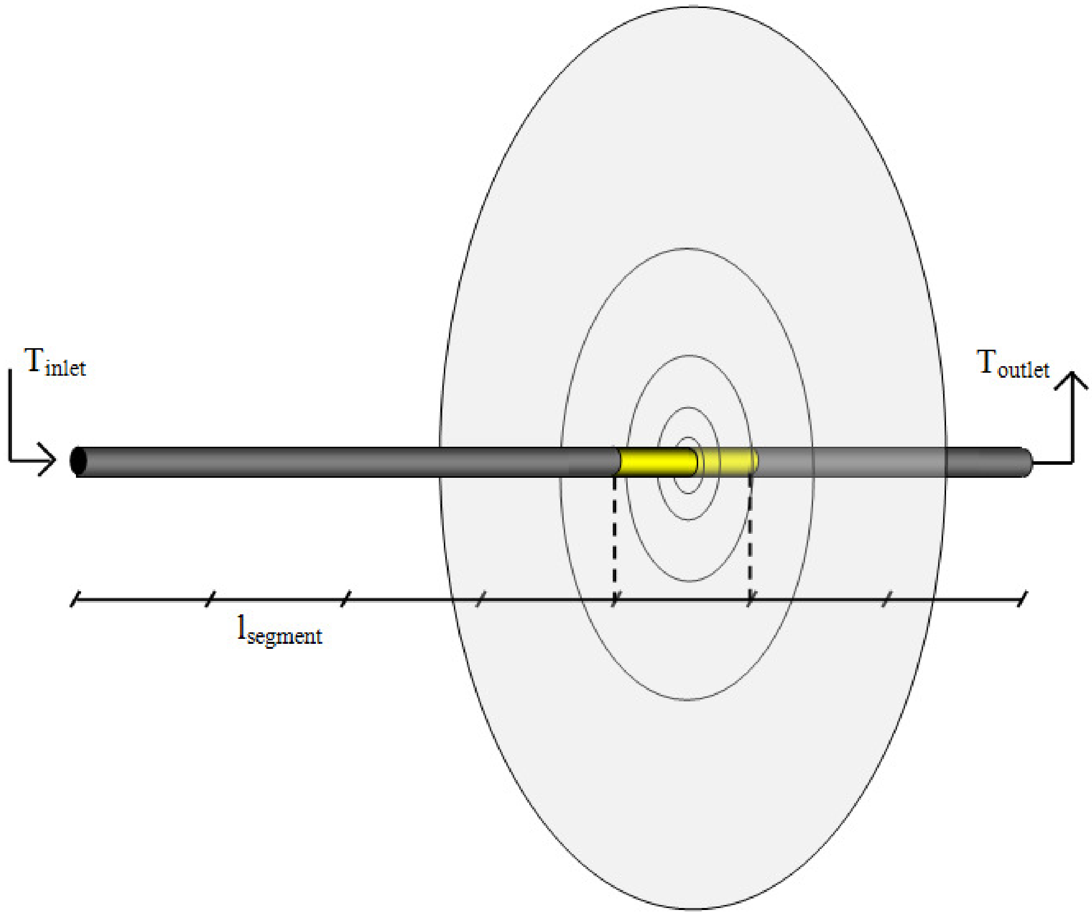


Figure 4.10 The ground is divided into several circular elements around each segment of the pipe, the circular elements is illustrated by the gray plate. The temperature is calculated in each element.

The radius of the element nodes, i.e. the radius of each circle in the figure, is increasing logarithmic with longer distance from the pipe. This is due to that the temperature varies more close to the pipe, which desires smaller elements. Far away from the pipe, the element does not have to be as small as close to the pipe. The logarithmic change of radius makes it possible to use fewer elements which increase the speed of the calculation. To calculate the temperature in each circular element, the conductance between the elements needs to be known.

4.3.1 Conductance's between the circular elements

The heat conduction is one dimensional in radial direction out from the pipe. The ground is divided into circular elements around each segment of the pipe, this is illustrated in Figure 4.11. The change of temperature is due to the change of energy for each time step in the element as well as the heat capacity of the element. The coupling between each circular element is the conductance. The conductance between two elements is one over the sum of half the resistance from each neighbouring elements.

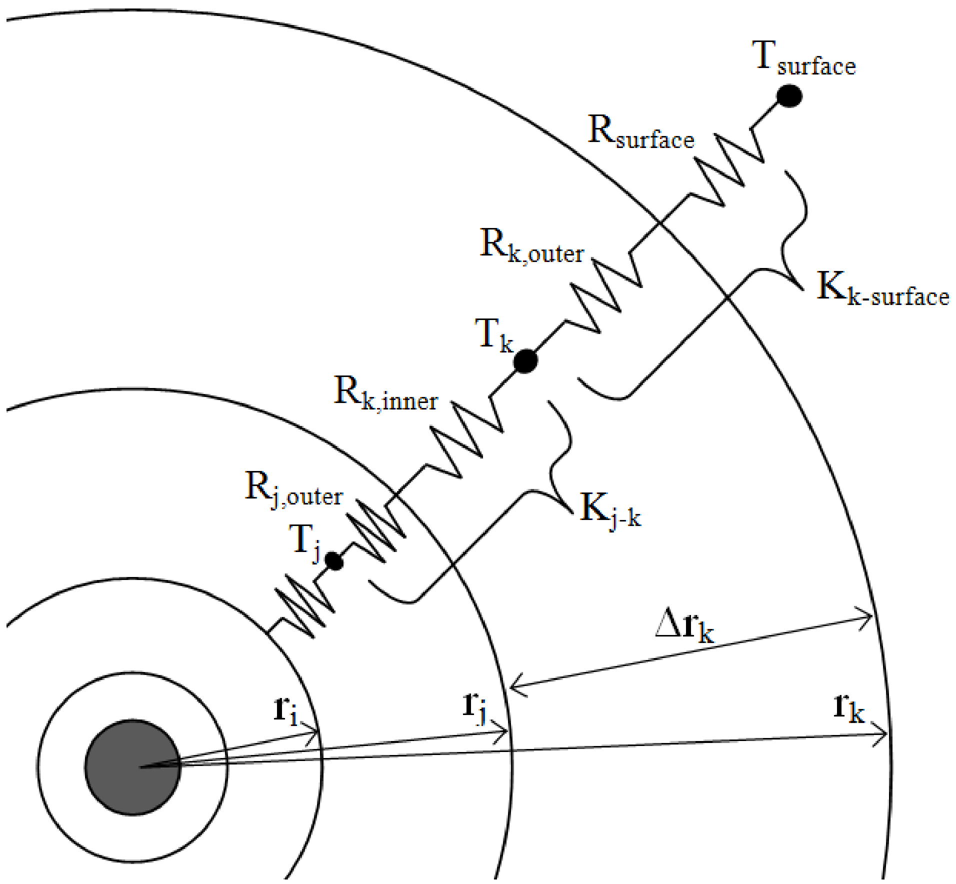


Figure 4.11An illustration of the circular elements around the pipe and how they are connected to each other with respect to heat conduction.

How the conductance between the non boundary elements and the inner and outer boundary elements are calculated is described respectively. (Wang, J. 1998)

Non-boundary circular elements

A non-boundary conductance is calculated with equation (4.29).

$$K_{j-k} = \frac{1}{R_{j,outer} + R_{k,inner}} = \frac{1}{\frac{ln\left(\frac{r_i}{r_i - 0.5\Delta r_i}\right)}{2\pi\lambda_i} + \frac{ln\left(\frac{r_i + 0.5\Delta r_j}{r_i}\right)}{2\pi\lambda_j}} \text{ [W/(mK)]} \qquad (4.29)$$

Inner boundary

At the inner boundary resistance between fluid and pipe is included as well as the resistance from half the first circular element. The conductance at the inner boundary is calculated with equation (4.30).

$$K_{fluid-1} = \frac{1}{R_{fluid-pipe} + R_{inner,1}} = \frac{1}{R_{fluid-pipe} + \frac{ln\left(\frac{r_{inner}+0.5\Delta r_1}{r_1}\right)}{2\pi\lambda_1}} \text{ [W/(mK)]} \quad (4.30)$$

The resistance between the fluid and the inner surface of the pipe, $R_{fluid-pipe}$, is calculated in equation (4.31). (Wang, J. 1998)

$$R_{fluid-pipe} = \frac{1}{\pi * \lambda_{fluid} * Nu} \text{ [mK/W]} \quad (4.31)$$

Nu, is the Nusselt number, and it depends on Reynolds number. Reynolds number tells the behavior of the flow, i.e. if the flow is laminar or turbulent.

$$If Re < 2300 \rightarrow Nu = 4 => laminar$$
$$If Re \geq 2300 \rightarrow Nu = 0.0023 * Re^{0.8} * Pr^{1/3} => turbulent$$

Reynolds number is calculated with equation (4.32).

$$Re = \frac{4\rho_{fluid}}{\pi\mu_{fluid}} * \frac{v_{fluid}}{2r_{inner}} \text{ [-]} \quad (4.32)$$

Were v_{fluid} [m^3/s] is the volume flow rate, ρ_{fluid} [kg/m^3] is the density of the fluid and μ_{fluid} [kg/(ms) or Ns/m^2] is the dynamic viscosity of the flow. Pr is Prandtl number and it is calculated with equation (4.33).

$$Pr = \frac{\mu_{fluid} c_{fluid}}{\lambda_{fluid}} \text{ [-]} \quad (4.33)$$

c_{fluid} [Ws/ (kgK)] is the heat capacity of the fluid. (Karlsson, H. 2010)

Outer boundary

At the outer boundary half of the most outer cylindrical element and the resistance up to ground surface are included in the conductance $K_{j\text{-surface}}$. The conductance outside the most outer element is calculated with equation (4.34)

$$K_{k-surface} = \frac{1}{R_{k,outer} + R_{surface}} = \frac{1}{\frac{ln\left(\frac{r_k}{r_k - 0.5\Delta r_k}\right)}{2\pi\lambda_k} + R_{surface}} \text{ [W/(mK)]} \quad (4.34)$$

$R_{surface}$ is the whole resistance for the remaining ground, which is the ground outside the most outer element, up to the surface. In this report it means the resistance for the remaining ground outside the element and a resistance due to insulation on the ground surface. At a distance from the pipe the heat flow will deviate from the radial direction and start to bend upward to the surface. Due to this another formula, equation (4.35), is used to calculate the resistance from the pipe up to the ground surface.

$$R_{pipe-surface} = \frac{1}{2\pi\lambda_{ground}} ln\left(\frac{2D}{r_{inner}}\right) \text{ [mK/W]} \quad (4.35)$$

D [m] is the distance to the ground surface and the equation is valied if $r_{inner} << D$. This resistance means the whole resistance from the pipe to the ground surface. Therefore the resistance for the ground already calculated in the cylindrical elements needs to be subtract before adding this term to $R_{surface}$. (Claesson, J., Dunand, A. 1983)

At top of the ground surface insulation is placed, that is the ground of the building. Above this insulation the temperature is known. The resistance for the insulation is calculated with equation (4.36) and theoretically seen as a ring with the thickness d_{ins}.

$$R_{ins} = \frac{1}{2\pi\lambda_{ins}} ln\left(\frac{D+d_{ins}}{D}\right) \text{ [mK/W]} \tag{4.36}$$

The resistance, $R_{surface}$ for the remaining ground to the known temperature at top of the insulation, can be calculated with equation (4.37). Were the total resistance from the pipe to the surface and the resistance due to the insulation is summed up and the resistance already calculated in the circular elements is subtracted.

$$R_{surface} = R_{pipe-surface} + R_{ins} - \sum_{1}^{j}(R_{inner} + R_{outer}) \text{ [mK/W]} \tag{4.37}$$

4.3.2 Heat flow between the elements

The heat flows for one circular element can be seen in Figure 4.12.

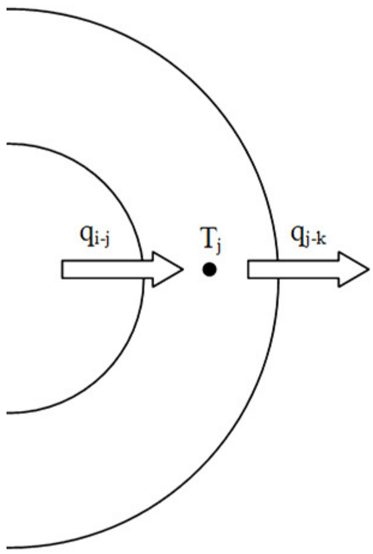


Figure 4.12 The heat flow in and out from element j.

The heat flows are further described for the non boundary elements and the inner and outer boundary elements respectively.

<u>Non-boundary circular elements</u>

The heat flow between the elements is calculated with equation (4.38).

$$q_{i-j} = K_{i-j}(T_i - T_j) \text{ [W/m]} \tag{4.38}$$

The difference in heat flow between the elements is calculated by using equation (4.39).

$$\Delta q_j = q_{i-j} - q_{j-k} \text{ [W/m]} \tag{4.39}$$

<u>Inner boundary</u>

At the inner boundary the heat flow, calculated with equation (4. 40), is dependent of the change in energy in the fluid.

$$q_{pipe-1} = \frac{v_{fluid}c_{fluid}\rho_{fluid}(T_{\text{seg}} - T_{seg+1})}{L_{seg}} \text{ [W/m]} \tag{4.40}$$

Were L_{seg} is the length of the segment. T_{seg} and T_{seg+1} is the inlet and outlet temperature for the current pipe segment.

The difference in heat flow for the inner element is calculated with equation (4.41).

$$\Delta q_1 = q_{pipe-1} - q_{1-2} \text{ [W/m]} \tag{4.41}$$

Outer boundary

For the outer boundary heat flow will be affected of the temperature at the surface. The heat transfer at the outer boundary is calculated with equation (4.42).

$$q_{k-surface} = K_{k-surface}\left(T_j - T_{surface}\right) \text{ [W/m]} \tag{4.42}$$

The change in energy for the most outer element is calculated with equation (4.43).

$$\Delta q_{\mathrm{k}} = q_{j-k} - q_{k-surface} \text{ [W/m]} \tag{4.43}$$

4.3.3 Temperature in each element

The change in temperature is due to the change of internal energy in the element and the heat capacity in the element for each time step. The change in temperature for element j is calculated with equation (4.44). (Hagentoft, C.-E. 2001)

$$\Delta T_j = \Delta t \frac{(\Delta q_{\mathrm{j}})}{\rho c_{j,ground} * \pi * \left(r_i^2 - r_j^2\right)} \text{ [°C]} \tag{4.44}$$

The new temperature for the same element is calculated with equation (4.45).

$$T_{j\_new} = T_{j\_old} + \Delta T_j \text{ [°C]} \tag{4.45}$$

4.4 The connection and interaction of building, pipe and ground

The models are put together by using a stable time step and calculating steady state in each sub system for each time step. The stable time step is decided by the behaviour in the ground and it is calculated in equation (4.46) (Hagentoft, C.-E. 2001). The stable time step is needed to avoid oscillations of the solution that hinders the temperature in each cell to converge. Suppose the time step to be to large in Figure 4.12. As long as T_i is bigger than T_j the heat flow q_{i-j} will go to the right. With a too long time step, the energy ($q_{i-j}*\Delta t$), is so big that ΔT in between the cells changes sign, that causes a oscillation of the solution. To be on the safe side, the stable time step has been multiplied with 0.95. That means 95 percent of the smallest time step is used as the stable time step in the calculations.

$$\Delta t_{stable} = 0.95 * \min\left(\frac{\left(r_i^2 - r_j^2\right)\pi\rho c_{j,ground}}{K_{i-j} + K_{j-k}}\right) \text{ [s]} \tag{4.46}$$

The procedure of the time dependent calculation can be seen in Figure 4.13. At first all data is loaded, this is for example geometry of the building, dimensions of the pipe, limits of temperatures and material data for walls, ground and fluids. The outside temperature and internal load should also be known for the whole calculation period.

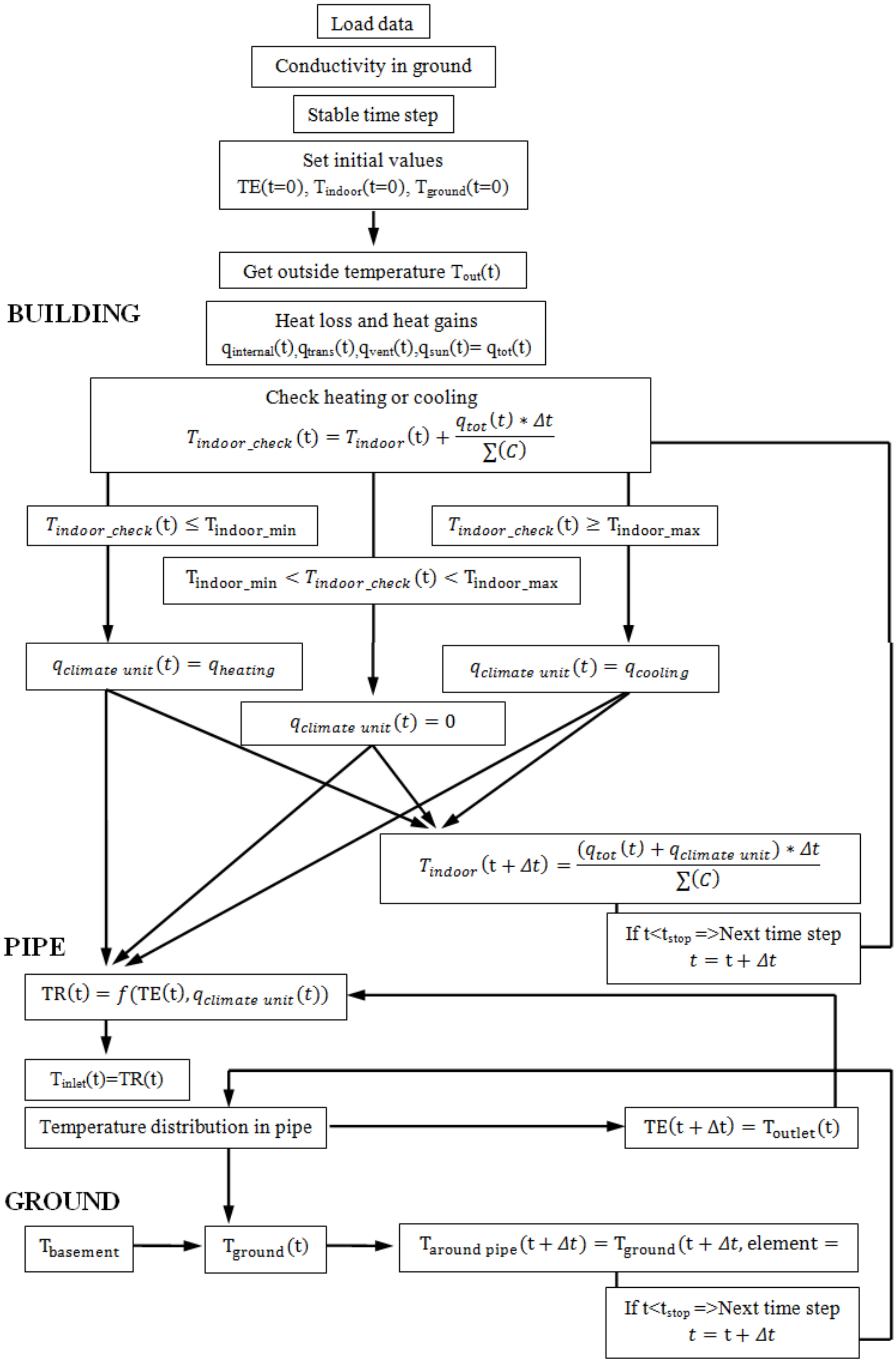


Figure 4.13 The time dependent calculation process. The demand for climate control is not dependent on the process in the storage system. Therefore the iteration process in the building can be separated from the pipe and ground system just to calculate the heating and cooling demands over time.

After importing the data, the conductivity in the ground in between the circular elements is calculated. The conductance's are not time dependent and are therefore calculated outside the time dependent loop which is initiated later in the procedure. When the conductivity is known the stable time step is calculated. To initiate the loop initial values need to be decided, that is the entering temperature to the climate unit, TE, the indoor temperature, T_{indoor}, and the temperature in the ground for each element, T_{ground} at time t=0.

In the loop the outside temperature is imported for the actual time step, and the temperature is interpolated if the values are given with too long time in between. Afterward the loss or gain of power due to transmission, ventilation and internal heat is calculated. The sum of this power is called q_{tot} and they cause a change in indoor temperature over the time step. The temperature change is added to the indoor temperature, which was calculated in the previous time step. Now the temperature called $T_{indoor\_check}(t)$ can be calculated. If $T_{indoor\_check}(t)$ is bigger, smaller or in-between the demands of the indoor temperature decides whether the climate unit is on cooling mode, heating mode or not in use. The mode on the climate unit decides, together with the entering temperature, $TE(t)$, to the climate unit, the return temperature, $TR(t)$, from the climate unit.

The return temperature, $TR(t)$, is the same as the inlet temperature $T_{inlet}(t)$ to the pipe. By knowing the ambient temperature around the pipe, i.e. the temperature in the most inner circular element of the ground for each segment of the pipe, the temperature distribution in the pipe can be calculated. The ambient temperature of the ground is calculated in the previous time step.

At this point the new temperature distribution in the ground is calculated. For each time step the temperature rearranges a bit according to the temperature in the previous time step, the temperature in the pipe and the temperature at the surface, $T_{basement}$. When the temperature in the ground is known, the loop goes on with the next time step, until the stop time, t_{stop}, is reached.

5 Analyse of the models used in calculations

The behaviour of the different parts of the mathematical model are studied in this chapter. In the first part the behaviour of the building is investigated. This investigation is made by adding the different kinds of energy losses or energy gains in the building to see that the indoor temperature responds as expected. The pipe model is analysed with the analytical equation for temperature distribution in a pipe. The model of the ground is compared with a result from calculation in a publication from Chalmers. Due to this analyse it can be seen that all the parts of the model act as expected or predicted.

5.1 Analyse of the behaviour of model of building

In Figure 5.1 the building is simulated for 10 days in summer. The curves show the indoor temperature except from the black one, which shows the outdoor temperature over these 10 days. If the only heat transport in the building is due to the ventilation and the air volume in the building is the only material with heat capacity, it can be seen that the indoor temperature follows the outdoor temperature. If the heat capacity of the walls is added, the variation in indoor temperature is damped. When a constant internal load is added the indoor temperature rises and the heat loss due to ventilation gets higher. The variation in indoor temperature has equal behaviour as the previous case. For the last case, which also includes transmission, a heat loss for the lower temperatures can be seen and the indoor temperature mainly lowers a bit.

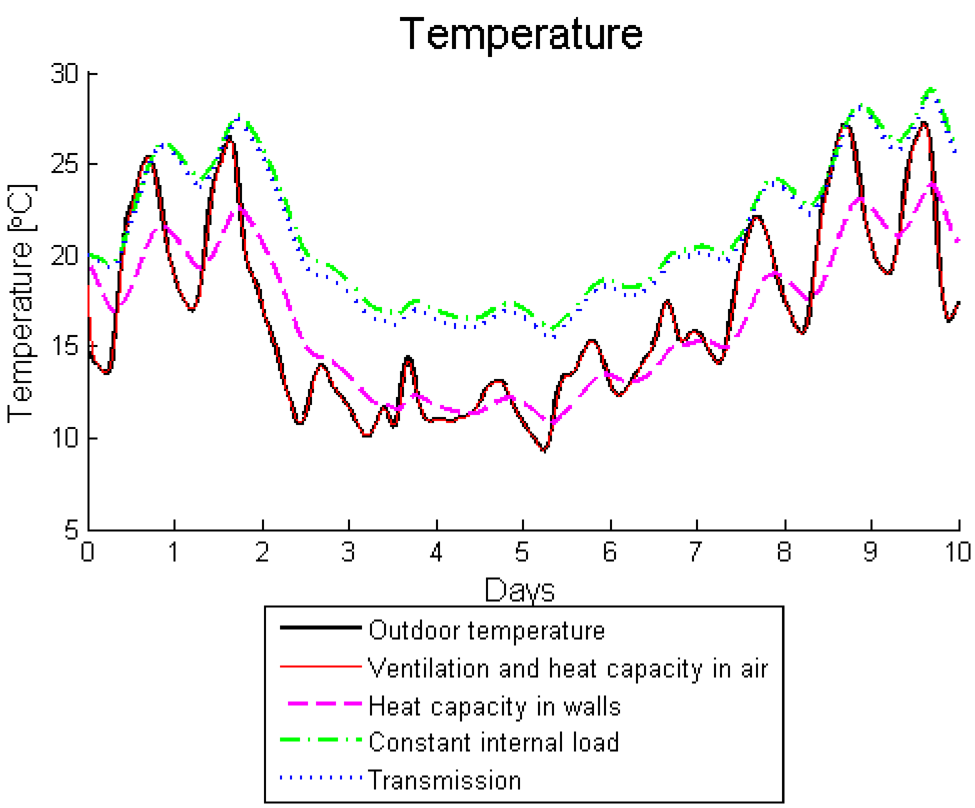


Figure 5.1 The behaviour of the indoor temperature when different kinds of heat gain or loss in the building is added.

5.2 Validation of temperature distribution in pipe

To analyze the behaviour of the model of the pipe a test case with constant ambient temperature and constant heat conductance between the pipe and the ambient temperature is used. The solution is calculated with equation (5.1). (Hagentoft, C.E. 2001)

$$T(x) = T_{ambient} + (T_{inlet} - T_{ambient})e^{-x/l_c} \text{ [°C]} \tag{5.1}$$

At what distance a certain temperature is reached is calculated with equation (5.2)

$$x(T) = -log\left(\frac{T - T_{ambient}}{T_{inlet} - T_{ambient}}\right) * l_c \tag{5.2}$$

For the test case an ambient temperature of 0° C and an inlet temperature of 1° C are chosen. The other properties used are v_{fluid}=0.1 (litre/s), c_{fluid}=4200 (Ws/kgK), ρ_{fluid}=1000 (kg/m^3) and a constant heat conductance of 0.15 (W/K) per unit length pipe. This gives a characteristic length of 2800 m.

For the given temperatures the temperature in the pipe at a certain distance is calculated with equation (5.3)

$$T(x) = e^{-x/l_c} \tag{5.3}$$

For a pipe which length is equal to l_c the outlet temperature calculated with equation (5.4)

$$T(l_c) = e^{-l_c/l_c} = e^{-1} = 0.37 \text{ °C} \tag{5.4}$$

A fluid temperature of 10% of the inlet temperature is for the given conditions reached at point calculated with equation (5.5).

$$x(T = 0.1T_{inlet}) = -log\left(\frac{0.1*1}{1}\right) * l_c = -log(0.1) * 2800 = 6450\, m \tag{5.5}$$

With the same conditions as above the calculated temperature distribution from the model can be seen in Figure 5.2. At the distance equal to the characteristic length the temperature has reach the value of 0.37°C, which is the equal to the temperature predicted by the calculations above. This value is shown by the dotted line in the figure. It can also be seen that the distance where 10% of the inlet temperature is at 6450 meter from the inlet, which is correct according to the calculations above.

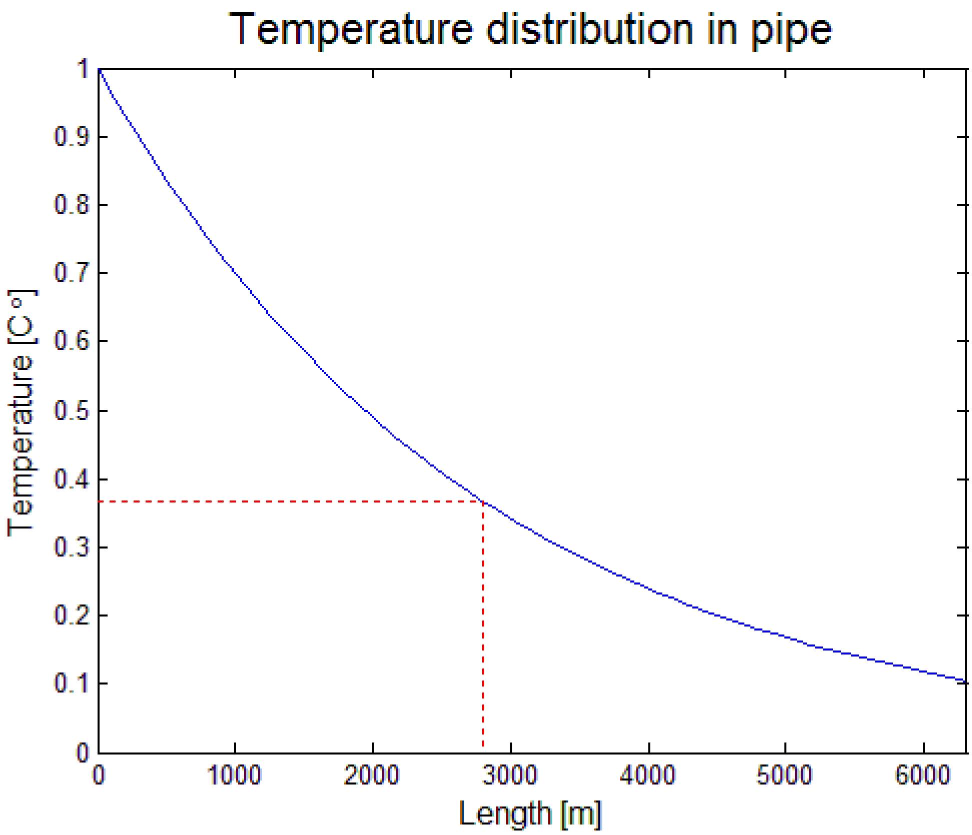


Figure 5.2 The temperature of the fluid over length of the pipe

5.3 Validation of model of ground

The model of the ground is compared with a numerical and analytical solution both presented in a publication from Chalmers. The calculation is made for a special case and the data used are

r_{outer}=1m	T_{outer}=0 °C
d_{pipe}=0.000001	q_{inner}=0 °C
$\rho_{ground}*c_{ground}$= 100000J/m^{3}K	$T_{initial}$(t=0)=0 °C
λ_{ground}=0.035W/mK	

The calculation is made for different gamma, calculated with equation (5.6), which with the constants given, only depends on the time of calculation.

$$\gamma = \frac{\lambda}{\rho c} * \frac{t}{r_{outer}^2} \tag{5.6}$$

The simulation is made for three different values of γ and the result from the ground model can be seen in Figure 5.3. As expected the temperature rises in the domain due to longer simulation time, i.e. bigger value of γ. The longest simulation time, for γ=0.3, is close to 10 days. (Wang, J. 1998)

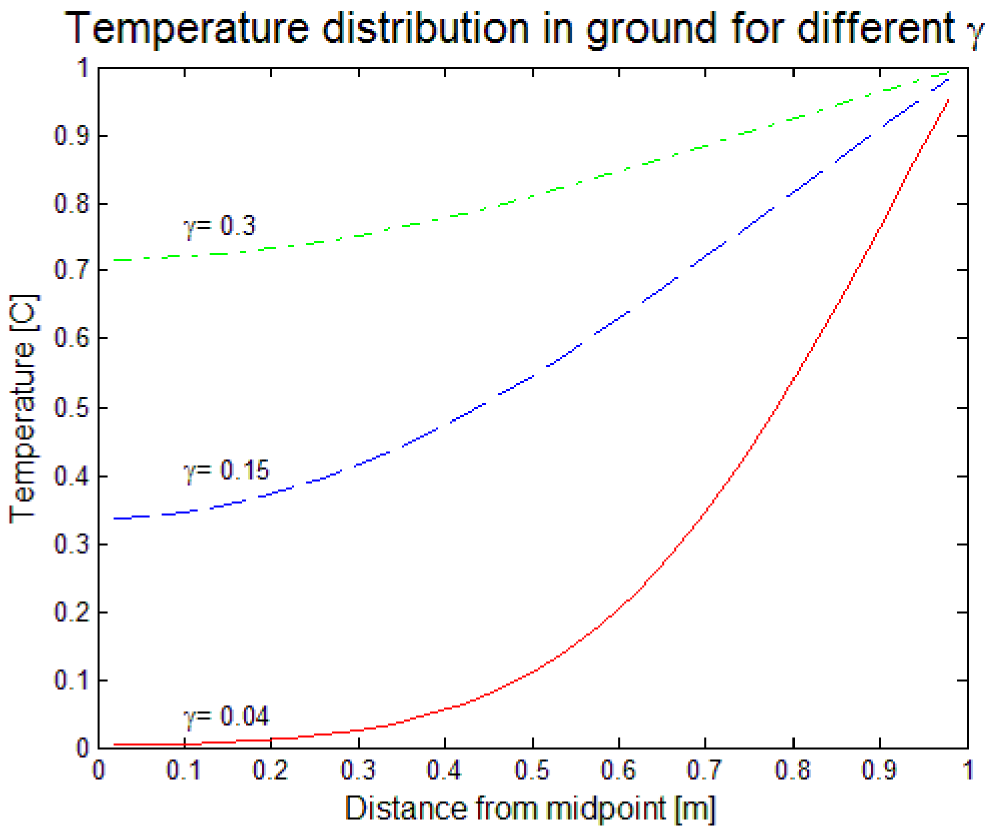


Figure 5.3 Temperature distribution in radial direction around the pipe for different γ

In Table 5.1 the result from the simulation of the different γ can be seen, as well as the solution from the numerical solution in the publication. The result differs only in a few points.

Table 5.1 Comparison between case calculated in (Wang, J. 1998) and the calculated result from the program.

Radius [m]	Temperature [C°]					
	γ=0.04 [-]		γ=0.15 [-]		γ=0.30 [-]	
	Simulation	Numerical	Simulation	Numerical	Simulation	Numerical
0,020	0,004	0,004	0,337	0,337	0,717	0,717
0,060	0,004	0,004	0,340	0,341	0,718	0,718
0,100	0,006	0,005	0,346	0,346	0,721	0,721
0,140	0,007	0,007	0,355	0,355	0,725	0,725
0,180	0,010	0,010	0,366	0,366	0,730	0,730
0,220	0,013	0,013	0,380	0,380	0,736	0,736
0,260	0,018	0,018	0,397	0,397	0,744	0,744
0,300	0,025	0,025	0,416	0,416	0,752	0,752
0,340	0,035	0,035	0,438	0,438	0,762	0,762
0,380	0,047	0,047	0,462	0,462	0,773	0,773
0,420	0,064	0,063	0,488	0,488	0,785	0,785
0,460	0,084	0,084	0,516	0,517	0,797	0,797
0,500	0,111	0,111	0,547	0,547	0,810	0,810
0,540	0,143	0,143	0,579	0,579	0,824	0,824
0,580	0,182	0,183	0,613	0,613	0,839	0,839
0,620	0,229	0,230	0,648	0,648	0,854	0,854
0,660	0,284	0,285	0,684	0,684	0,869	0,869
0,700	0,347	0,348	0,721	0,721	0,885	0,885
0,740	0,418	0,419	0,759	0,759	0,900	0,900
0,780	0,496	0,497	0,797	0,797	0,916	0,916
0,820	0,581	0,580	0,835	0,835	0,932	0,932
0,860	0,671	0,670	0,873	0,873	0,948	0,948
0,900	0,764	0,765	0,910	0,910	0,963	0,963
0,940	0,859	0,860	0,947	0,947	0,978	0,978
0,980	0,954	0,954	0,983	0,983	0,993	0,993

6 Description of the system used as the reference system.

The simulation of the storage and the building are made for a system described in this chapter. The detailed input data for the system and the building can be found in Appendix 1. In this chapter the main input data and motivation to choices that are made for the technical systems are presented.

6.1 Short information about the building and the surrounding

The building used in the calculations can be seen in Figure 6.1. It is a 70 times 70 square meter building with 3 floors. Each floor has a height of 3.5 meter and the thickness of the wall which can storage heat is 10 cm and it covers the outer walls.

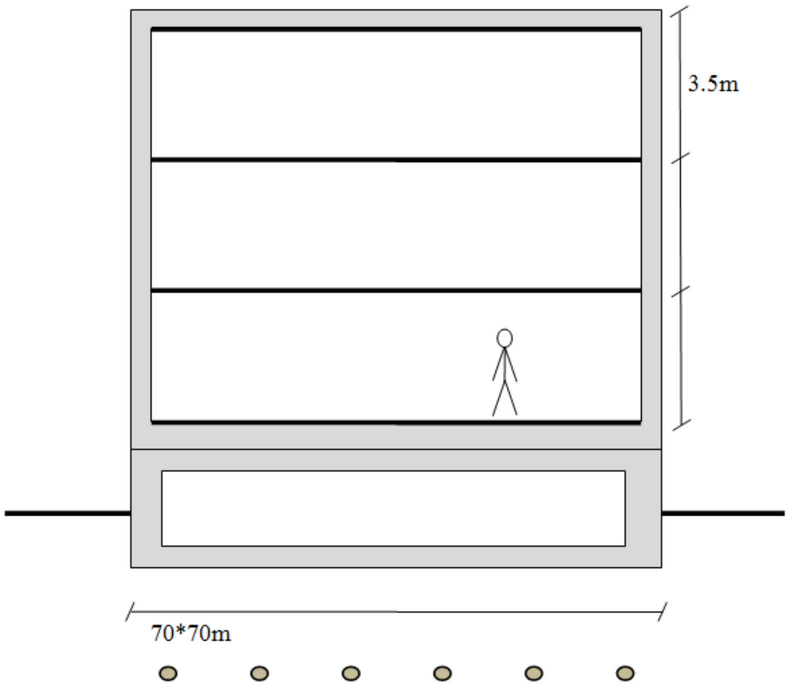


Figure 6.1 A sketch of the building used in the calculations. The pipe system may be placed under the building.

The internal load is the same whole year around but varies over the day. Its more internal loads during daytime, when there is actives in the building, and less internal loads during night. The ventilation rate has two modes; full ventilation during daytime and lowered ventilation during night. The daytime is between 6 in the morning and 6 in the evening. The outdoor temperatures and the loads due to sunshine are imported from a data file that gives values for each hour. The temperature limitations in the system are chosen to avoid problems, for example problems with freezing of ground and condensation in the cooling unit.

6.2 Calculation of COP for the heat pump

For the heating system the coefficient of performance is calculated, which is constant during the calculation period. If the heating system works at a higher temperature of 55°C and a lower temperature of 8°C the equation (6.1) calculates the COP_c. About 50% of this theoretical COP_c can be used in practice. (Lindholm, T. 2009)

$$\mathrm{COP_c} = \frac{T_1}{T1-T_2} = \frac{273+55}{273(55-8)} = 6.97 \tag{6.1}$$

Using 50% of COP_c=>COP=3.5

A COP of 3 is used in the calculations to be on the safe side.

6.3 Choice of volume flow in each pipe

The choice of volume flow rate in the pipes will be made according to some normaly used limitations for pipes. One limitation is that the losses due to friction should not be more than 100 Pa/m, this is a conventionally used maximum value for pressure loss in pipes. To avoid standing air bubbles in the pipes, the minimum flow rate is 0,2m/s. (Installationsteknik 2003)

The pipes in this system will be plastic pipes with inner diameter of 0.35 mm. By studying the diagram for friction loss for pipes of cupper, which has the same surface roughness, k=0.01 mm, as pipes of PVC, the maximum flow to avoid friction loss over 100 Ps/m for a pipe with inner diameter of 0.035 mm, is 0.5 l/s. Thus this diagram is for water in a higher temperature range (60-110°C), to be on the safe side the volume flow rate used in the calculations will be 0.45 l/s in each pipe. The volume flow rates will still manage the minimum flow rate to avoid air bubbles, see equation (6.2). (Installationsteknik 2003)

$$\frac{\mathrm{v}}{\mathrm{d}_{\mathrm{inner}}^2/(4\pi)} = \frac{0.45/1000}{\frac{0.035^2\pi}{4}} = 0.4677\mathrm{m/s} > 0.2m/s \tag{6.2}$$

A pump that is in a reasonable size can handle up to total 5000 Pa. That means the length of the pipe can for maximal flow be at maximum 500 m. To have some pressure available for turns and other details causing extra losses the pipe length is chosen to 400 m.

7 Results from the calculations

The results from the calculations are presented in this chapter. In Section 7.1 the heating and cooling demand for the building is described. In Section 7.2 the demands for the 24-hour storage are calculated and the design of the storage is made. Section 7.3 presents the results from the demands and design of the 1-year storage. Finally Section 7.4 shows the response of the heat storage due to different surface temperatures.

7.1 Cooling and heating demands in building over the year

The cooling and heating demand over the year are in this section described in two subsections. First the cooling and heating demand is described in section 7.1.1 for the original building. The demands in that section are also the demands which the results in the next chapters are based on. In the Sections 7.1.2-7.1.5 the input data from the original situation in building has been changed in different ways, to see how it influences the heating and cooling demand.

7.1.1 Cooling and heating demand of the building used in the calculation

By calculating the demand of power for the climate unit at each time step the variation of heating and cooling demand over the year can be seen. The demands are the same no matter the system for used supplying the demand. I.e., the demands in the building are the same no matter heat and cool storage system is used or not.

In the Figure 7.1 the outdoor temperature and the variation of the indoor temperature, with the demands between 21 and 23 degrees, can be seen over the year. In the lower diagram the mode on the climate unit is shown. From day 0, i.e. the start of the first day in January, and about 50 days further the climate unit mostly works on heating mode and turned off mode. That means, if using energy storage over this period, energy is only extracted from the storage. From day 50 to 150 both cooling and heating mode is needed, during this period it may be possible to both extract and return energy to the ground. During summer, from day 150 to day 250 there is only need for cooling and turned off mode. After day 250 the autumn starts and it is again a period of both cooling and heating. When it gets colder in the end of the year there is only need for heating mode and turned off mode on the climate unit.

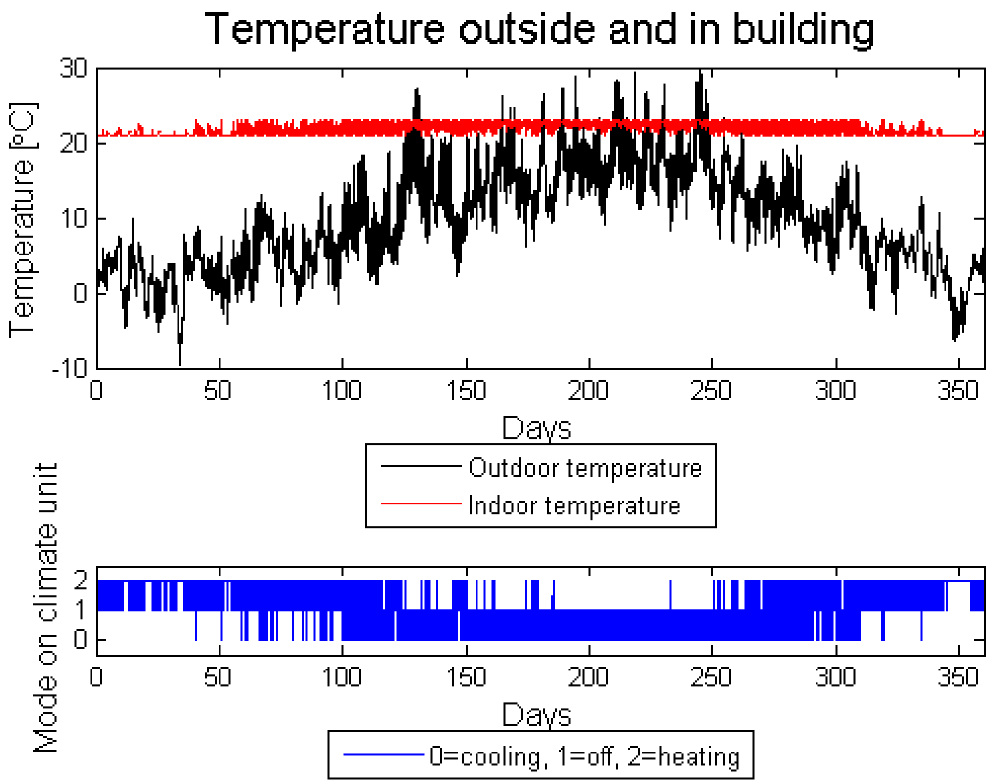


Figure 7.1 In the upper diagram the outdoor and indoor temperature is shown. In the lower diagram the mode, needed to keep the indoor temperature between the limits, on the climate unit is shown. (Day 0=1 of January)

The power the climate unit need to work on is illustrated in Figure 7.2 were the red part, above zero, is a heating demand, and the blue part, below zero is a cooling demand.

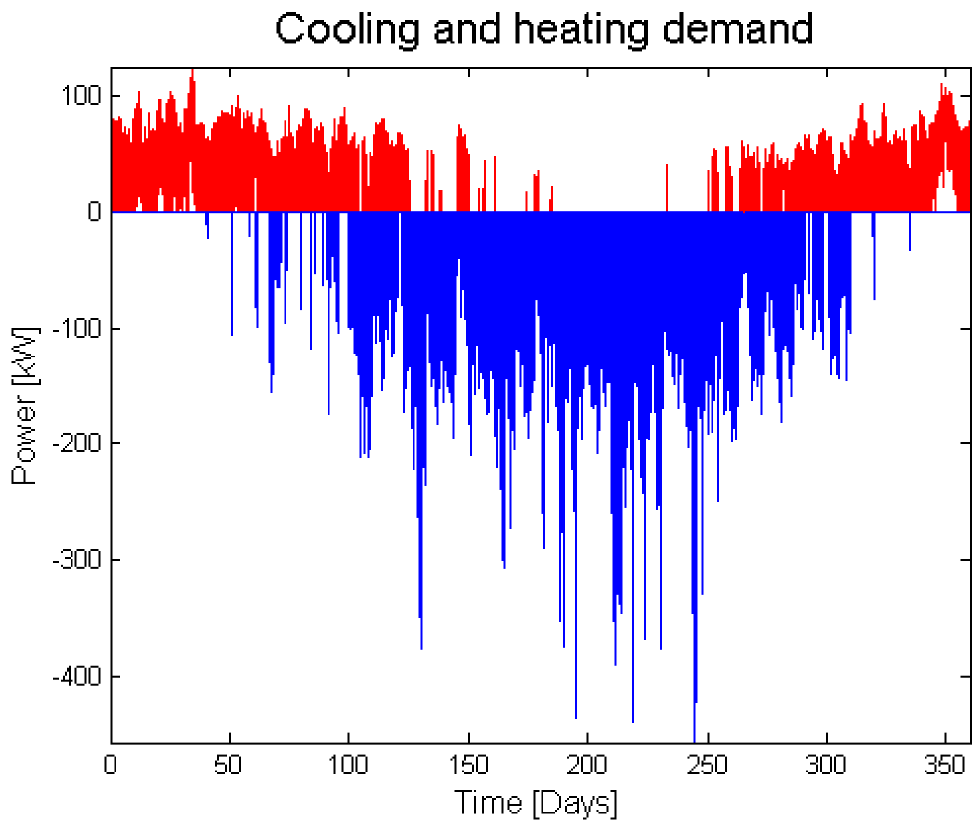


Figure 7.2 The diagram shows the power needed for heating (red marked and above zero) and the power needed for cooling (blue marked and below zero). (Day 0=1 of January)

By visually studying Figure 7.2 or the lower diagram in Figure 7.1 it can be seen that the period when heating is in use is about the same time length as the time length when cooling is in use. But it can be seen that the maximum cooling power is bigger than the maximum heating power. By summing the heating and cooling demand up over the year it can be seen that more cooling energy than heating energy is used. The total use of cooling and heat energy during this calculation period is

Heating: 150000 kWh

Cooling: -210000 kWh

That means a heating demand per square meter floor area and year of:

Heating: 10.5 kWh/(m^2,year)

Cooling:-14.8 kWh/(m^2,year)

This difference in amount energy needed for cooling and heating is also illustrated in Figure 7.3 were the energy, due to the cooling and heating power for each time step, is summed up over time. Since the curve ends below zero the building has a greater cooling demand than heating demand over the year.

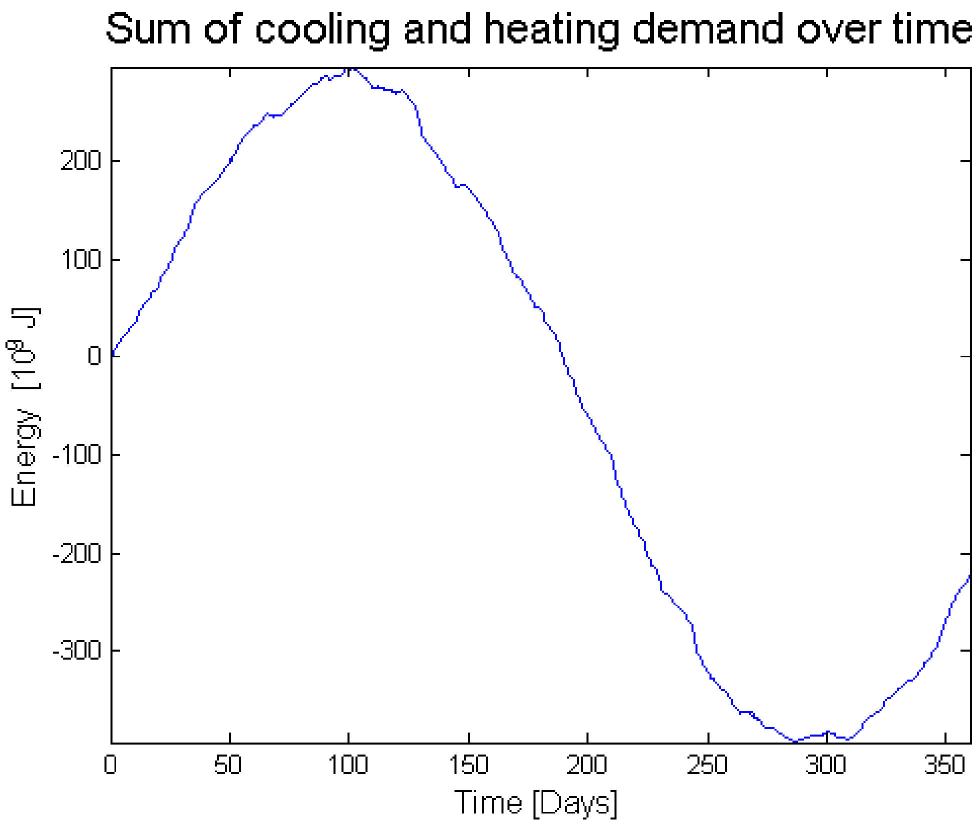


Figure 7.3 Sum of cooling and heating demand over the year. Since the curve ends below zero the cooling need is greater than the heating need. (Day 0=1 of January)

7.1.2 Variation of input data - Wider requirements on indoor temperature

If using wider requirements of the indoor temperature the length of the period with varying demand of heating and cooling over the day is decreasing. In the calculation the indoor temperature demand is between 20 and 24 instead of 21 and 23 as for the calculations in section 7.1.1. In Figure 7.4 it can be seen that it is only a few times over a short period in spring and in autumn the demand is changing between heating and cooling on a 24-hour basis.

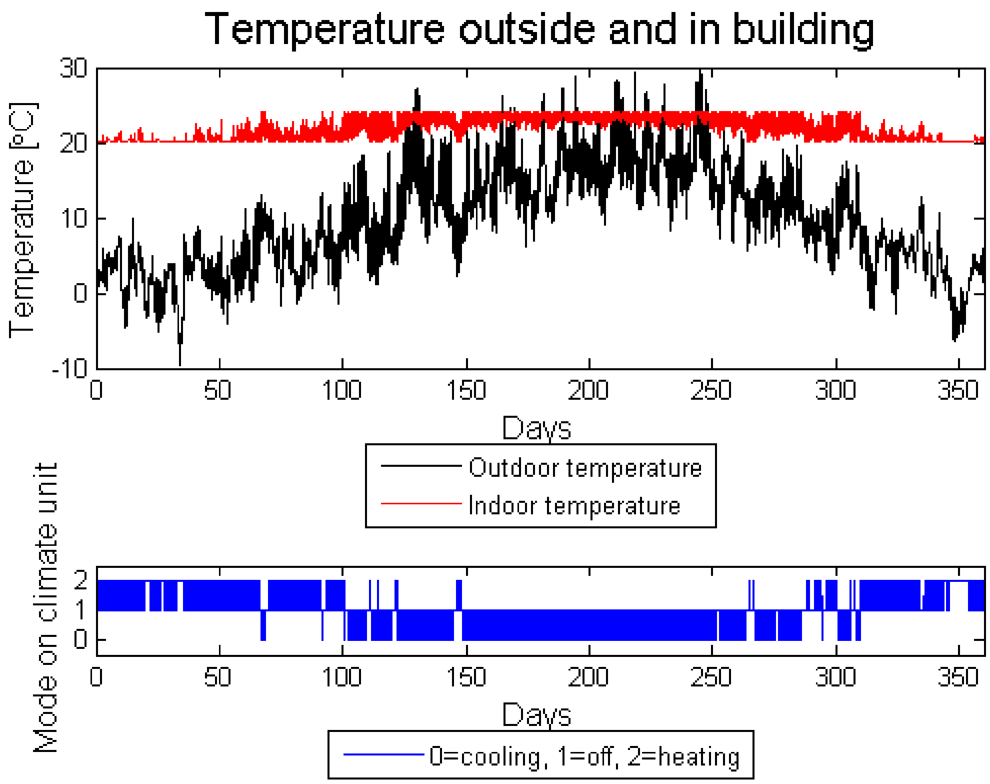


Figure 7.4 In the upper diagram the outdoor and indoor temperature is shown. In the lower diagram the mode, needed to keep the indoor temperature between the limits, on the climate unit is shown. It can be seen that the period during spring and autumn with variation between heating and cooling demand over a 24-hour basis is shorter (almost not existing) then for the original case in Figure 7.1 (Day 0=1 of January).

In Figure 7.5 it can also be seen that the cooling and heating are more separated from each other compared with Figure 7.2 in previous chapter. The maximum power of both heating and cooling are about the same as the powers calculated in previous section.

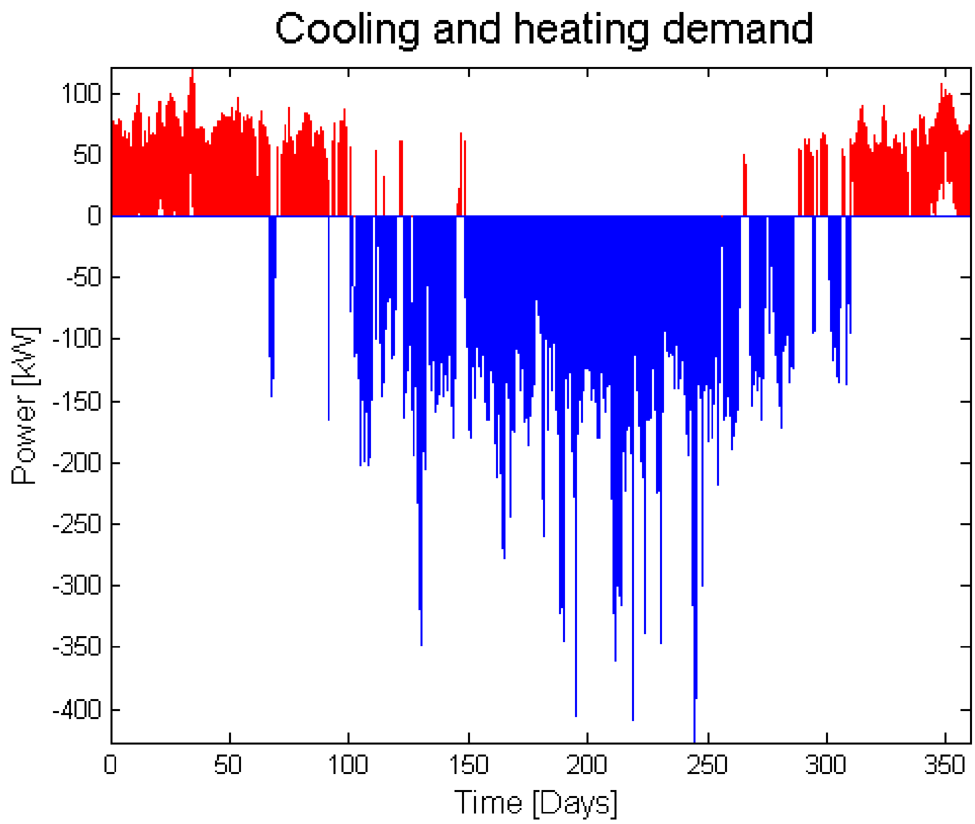


Figure 7.5 The diagram shows the power needed for heating (red marked and above zero) and the power needed for cooling (blue marked and below zero). It can be seen that the need of cooling energy is greater than the need of heat energy. (Day 0= 1 of January)

7.1.3 Variation of input data - Doubled internal loads

If doubling the internal loads the period with both heating and cooling increases but it is only the cooling energy part that is increasing over the year. For this situation there are a long period of the behaviour with heating during days and cooling during nights, it is only a period during summer where it is only cooling without heating. This can be seen in Figure 7.6.

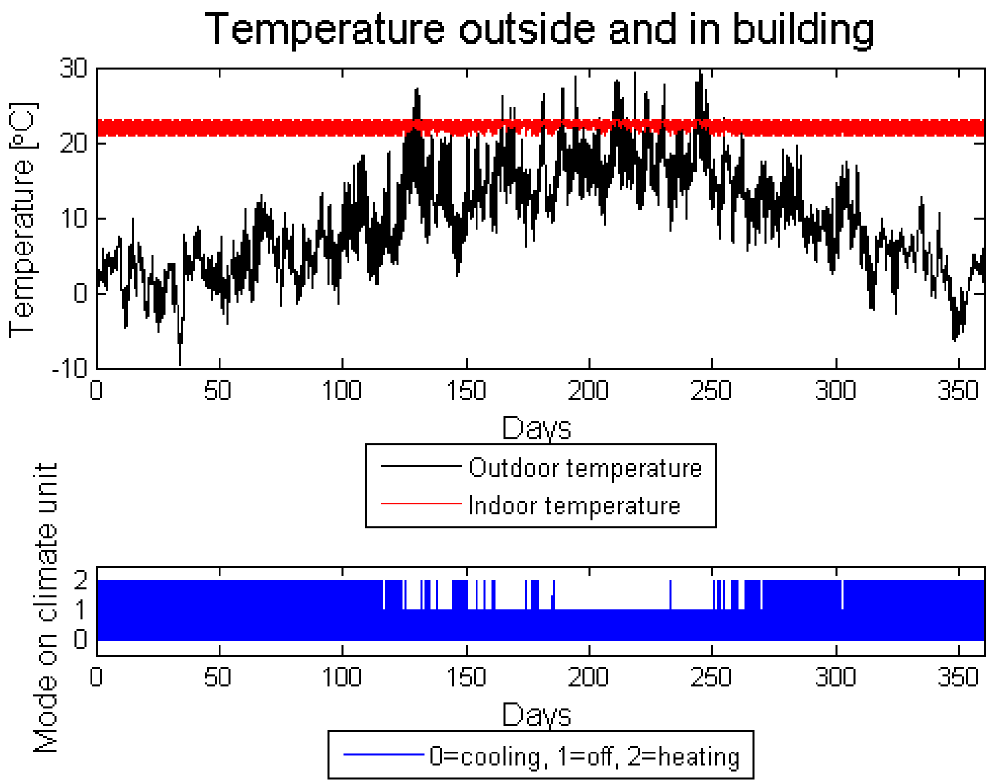


Figure 7.6 In the upper diagram the outdoor and indoor temperature is shown. In the lower diagram the mode, needed to keep the indoor temperature between the limits, on the climate unit is shown. It can be seen in the lower diagram that there is a change between demand of cooling and heating on a daily basis a long time of the year. It is only during summer it is a need of only cooling without heating. (Day 0= 1 of January)

In Figure 7.7 it can be seen that the demand of cooling energy and power has increased markedly. The maximum cooling power has increased with about 200 kW and energy needed for cooling over the year has also increased.

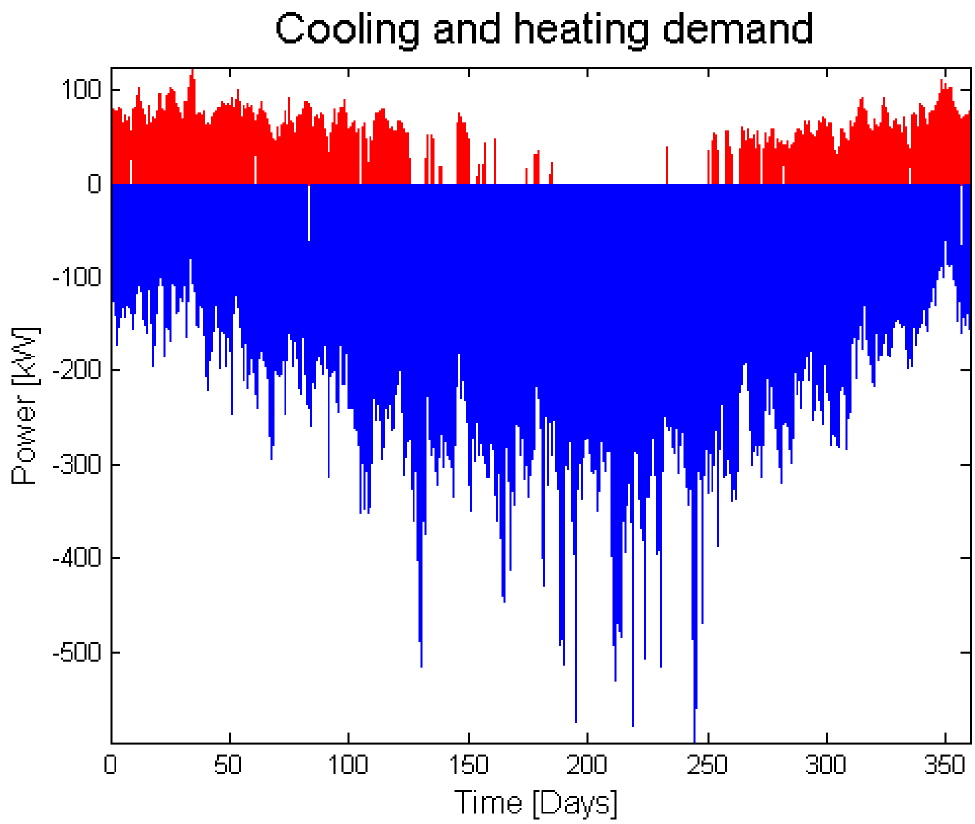


Figure 7.7 The diagram shows the power needed for heating (red marked and above zero) and the power needed for cooling (blue marked and below zero). It can be seen that the need of cooling energy is has increased allot compared with Figure 7.2. (Day 0= 1 of January)

7.1.4 Variation of input data - Doubled heat capacity

If the heat capacity in the building is doubled it can be seen in Figure 7.8 that about the same change of the cooling and heating demand happens if the requirement of the indoor temperature is wider, as in section 7.1.2. The period of cooling and heating demand varying over day to night is short compared with the calculations in section 7.1.1.

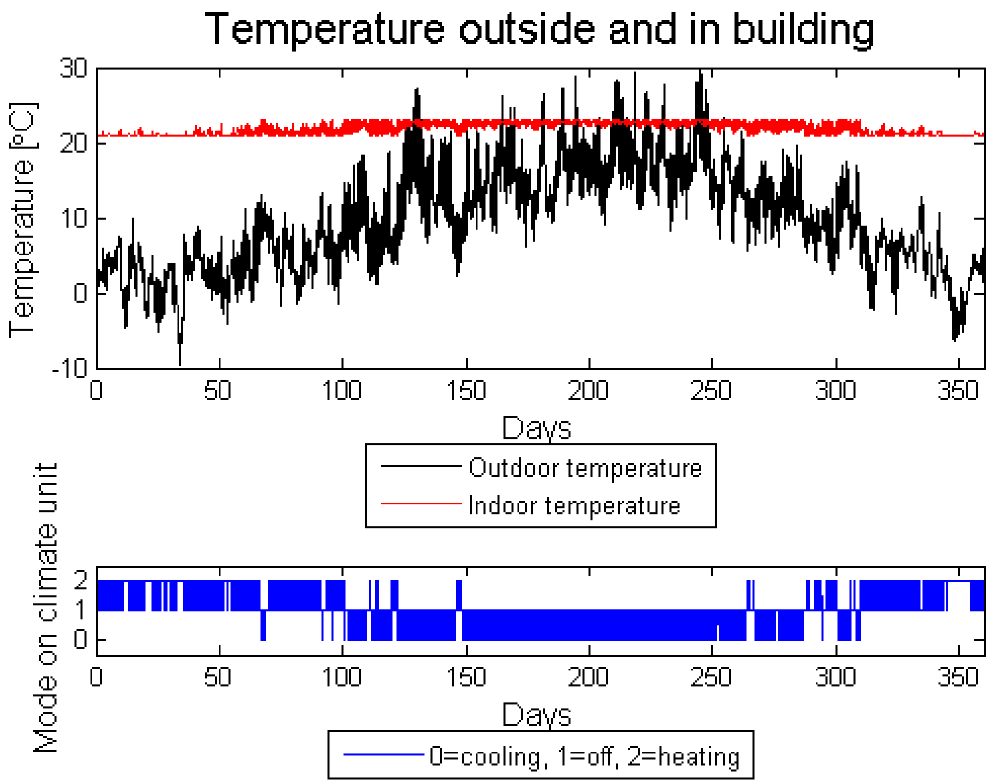


Figure 7.8 In the upper diagram the outdoor and indoor temperature is shown. In the lower diagram the mode, needed to keep the indoor temperature between the limits, on the climate unit is shown. It can be seen in the lower diagram that due to more heat capacity in the building the time that have a change of heating and cooling over a daily basis is shorter. (Day 0= 1 of January)

In Figure 7.9 it can be seen that the period with demand for cooling or heating are more distinct separated from each other compared with Figure 7.2.

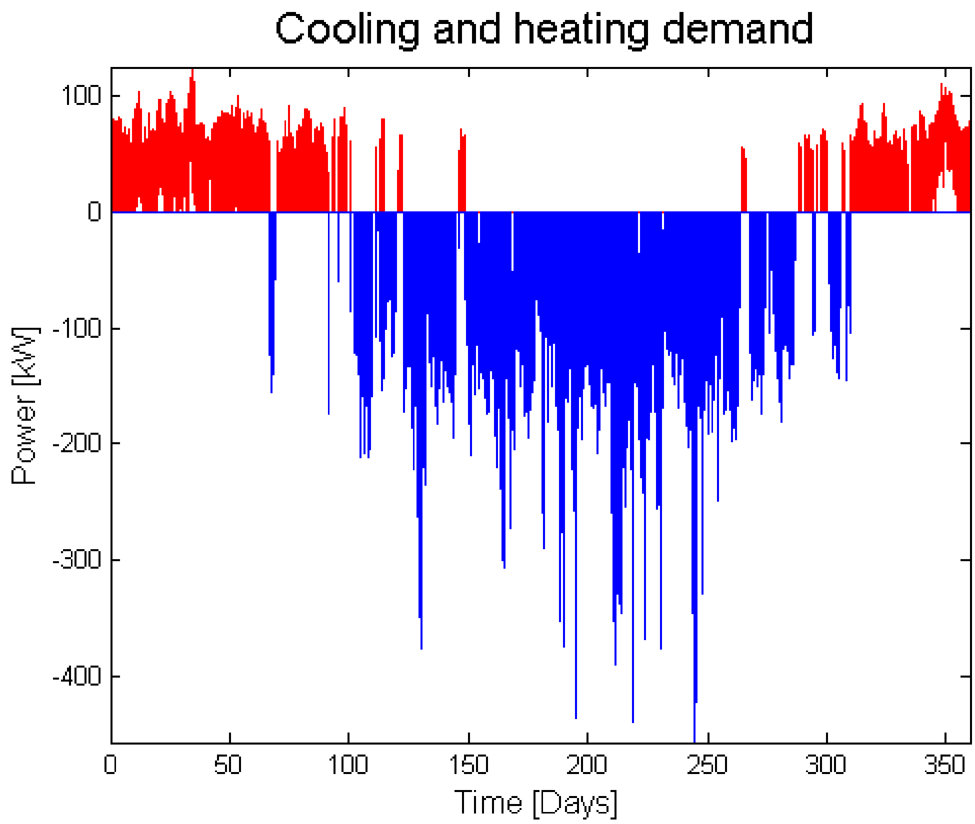


Figure 7.9 The diagram shows the power needed for heating (red marked and above zero) and the power needed for cooling (blue marked and below zero). It can be seen that the need of cooling energy is greater than the need of heat energy and the cooling and heating demand are separated from each other with respect to time. (Day 0= 1 of January)

7.1.5 Variation of input data - No sun included

If the sun is not included in the calculation it can be seen that there is a longer period of heating need during days. Compared with Figure 7.1 it can be seen in Figure 7.10 that the demands for cooling starts later in the year and that there is a longer period with a constant heating need during winter.

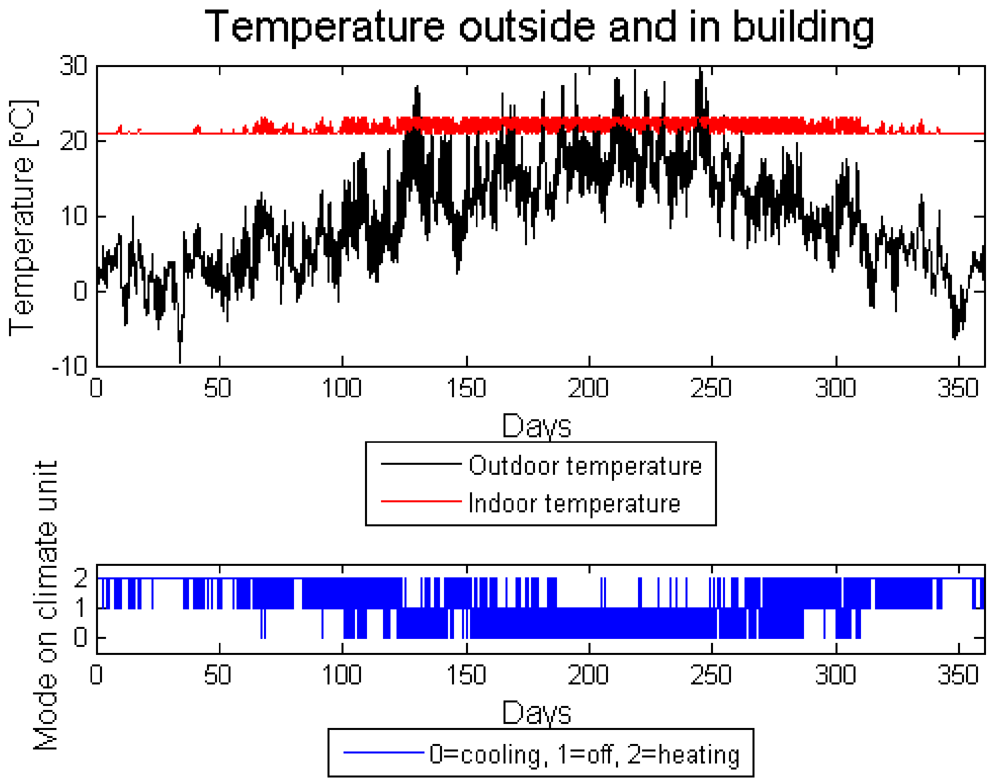


Figure 7.10 In the upper diagram the outdoor and indoor temperature is shown. In the lower diagram the mode, needed to keep the indoor temperature between the limits, on the climate unit is shown. When the insolation is not included there are longer times with constant heating during winter. (Day 0= 1 of January)

Figure 7.11 shows that the maximum power needed for cooling is lowered compared with Figure 7.2. The energy needed for cooling is lowered due to shorter cooling period and smaller powers. The energy needed for heating has increased due to longer period of heating, but the maximum heating power remains about the same as the one in calculated in section 7.1.1 and shown in Figure 7.2.

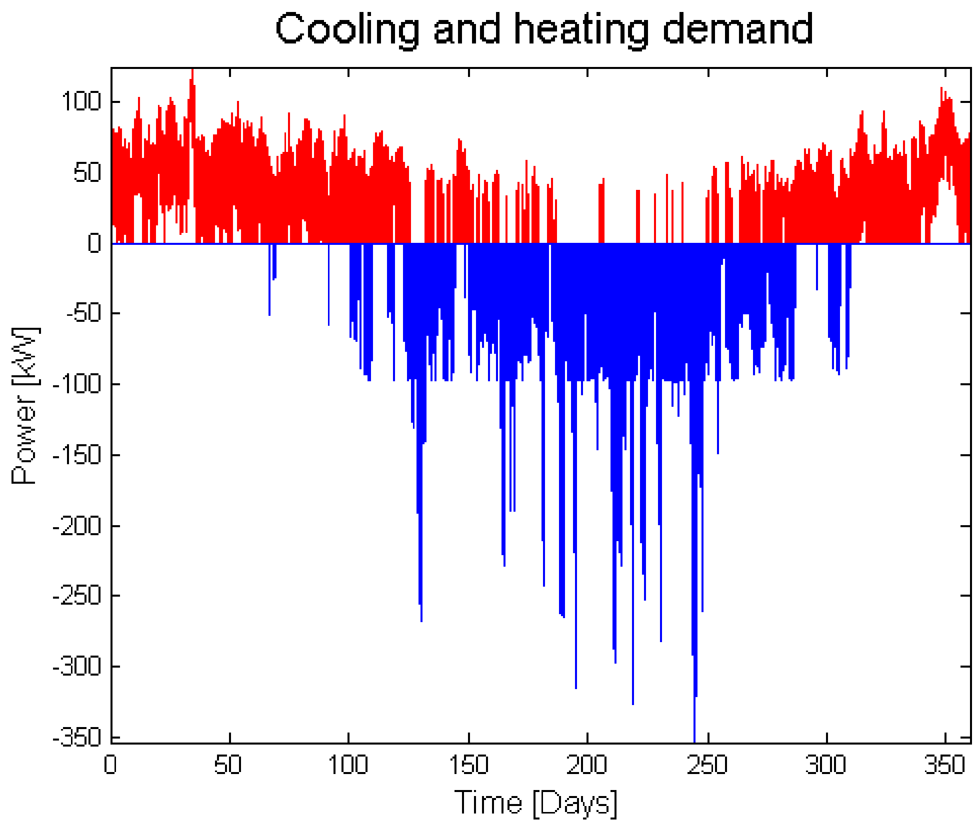


Figure 7.11 The diagram shows the power needed for heating (red marked and above zero) and the power needed for cooling (blue marked and below zero). It can be seen that the need of cooling energy is about the same as the need of heat energy but the maximum cooling power needed are still higher than the heating power. (Day 0= 1 of January)

7.2 Demands and design of 24-hour storage

In this section the thermal energy storage on 24-hour basis will be designed. The design of the energy storage is made for demands on climate control from calculations in Section 7.1.1. These are demands due to the original situation for the object. For the 24-hour storage the demand of cooling or heating need to vary from day to night. According to Figure 7.1 in Section 7.1.1 a behaviour like this can be seen in spring and in the autumn. Therefore the design the energy storage over 24-hour basis is made for a period of 20 days. This time period has characteristics days with demand of both cooling and heating varying over day and night.

It is important that the energy released from the ground is equal to the energy entering the ground. Therefore the demands of the characteristic days will be modified to be equal. This modification is made to not require too much energy from the storage that can't be returned later, or the other way around. Due to insure long term use of the storage this modification of the demands is made. The demand of cooling or heating that aren't required from the storage is covered with another system. The design of the storage is made for these modified characteristic days and the calculations are repeated to see the long term response.

7.2.1 Cooling and heating demand over 20 characteristic days

In Figure 7.12 a characteristic period suitable for designing the 24-hour storage is shown. The suitable period is 20 days long and starts at day 100, about middle of April. The variation of the, indoor and the outside temperature over these days can be seen in Figure 7.12. In the lower diagram it can be seen that the demands for cooling and heating varies between day and night all over the period.

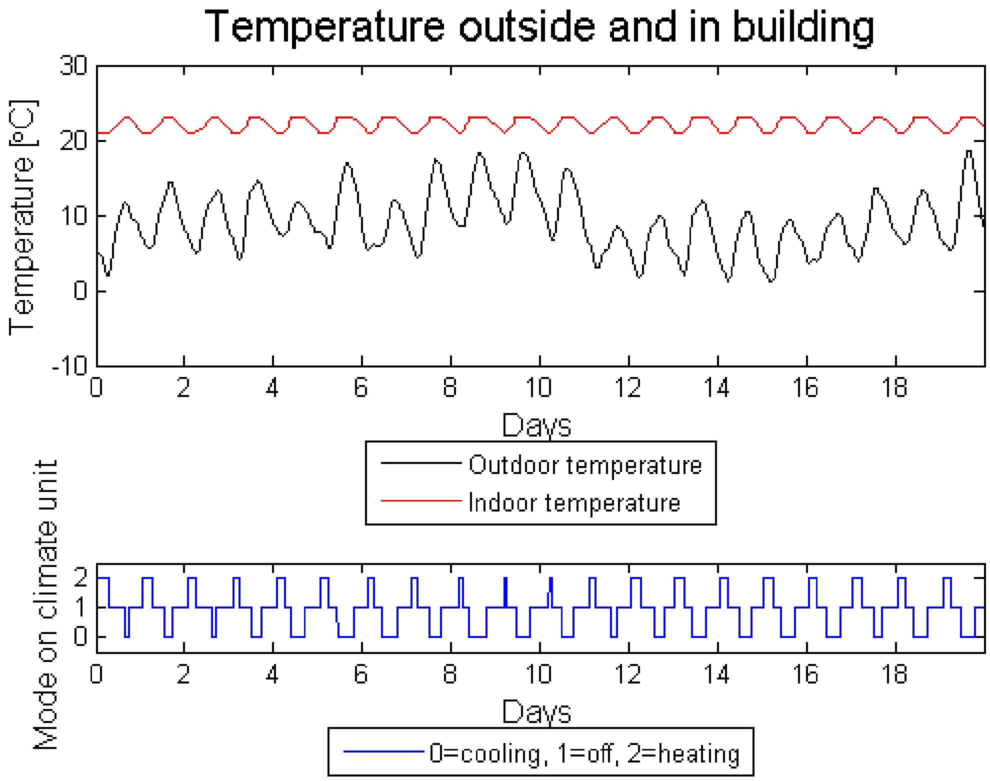


Figure 7.12 In the upper diagram the outdoor and indoor temperature is shown. In the lower diagram the mode, needed to keep the indoor temperature between the limits, on the climate unit is shown. It can be seen that the mode on the climate unit varies between cooling and heating every day and night over the period. (Day 0= Day 100 of the year, i.e. in middle of April)

In Figure 7.13 the cooling and heating power for this period is shown. It can be noticed that the power for cooling is greater and used over slightly longer time periods.

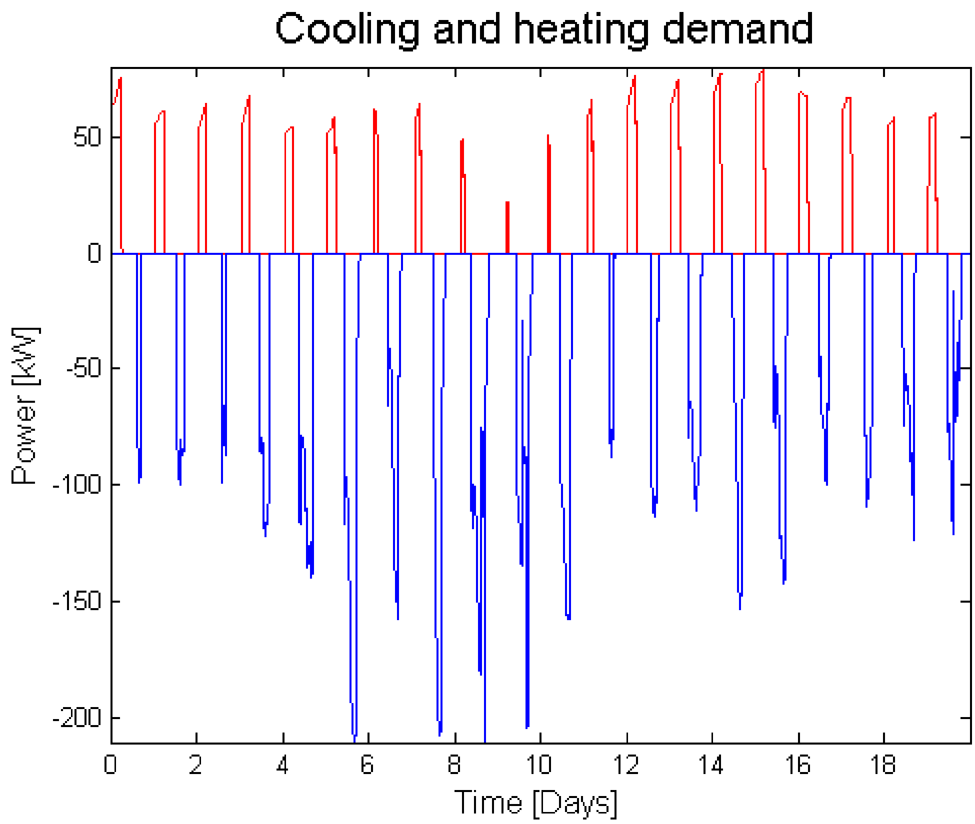


Figure 7.13 The diagram shows the power needed for heating (red marked and above zero) and the power needed for cooling (blue marked and below zero). It can be seen that the need of cooling energy and power is greater than the need of heat energy and power over the period. (Day 0= Day 100 of the year, i.e. in mid April)

Due to greater power of cooling and to the longer total time of the use of cooling than heating the energy needed for cooling is expected to be bigger for the time period. The total demand of cooling and heating during these 20 days is

Heating: 4800 kWh

Cooling: -11000 kWh

If this period is translated to be valid a whole year the energy use per square meter floor area and year due to climate control is:

Heating: 6.0 kWh/(m^2,year)

Cooling: -14.1 kWh/(m^2,year)

The sum of cooling and heating energy is illustrated in Figure 7.14. As you can see the curve ends below zero, i.e. the energy needed for cooling is bigger than the energy needed for heating.

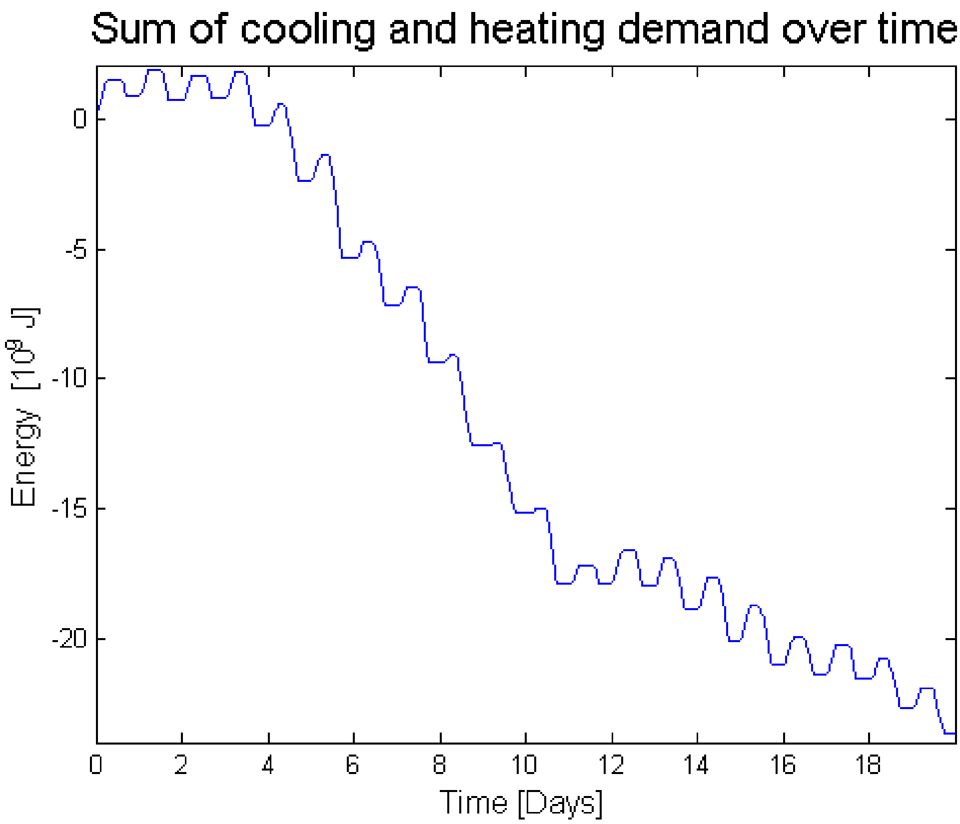


Figure 7.14 Sum of cooling and heating demand over the year. Since the curve ends below zero the cooling need is greater than the heating need over the period. (Day 0=1 of January)

7.2.2 Modified climate control demands for the characteristic days

To calculate the behaviour of the thermal energy storage, the demands on outtake of energy and demand on energy returning to the storage should be the equal. The solution for the calculations is to lower the cooling demand, so the sum of energies in cooling and heating mode is zero.

In Figure 7.15 the demand on cooling and heating and the modified demand on cooling and heating can be seen. The red line is the line for the heating demand and the blue is the line for the cooling demand, the same as in Figure 7.13. Only a part of the heating demand is released from the ground, this due to use of electricity that also gives heat energy, in the heat pump. Therefore only a part of the heat energy is taken from the ground. The energy taken from the ground is illustrated with the black line. The sum of the energy under the black line is compared with the sum energy needed for the cooling. In this case the heat energy is about 28% of the cooling energy. That means that 28% of the energy needed for cooling can be required from the storage, this part is illustrated with the green line in the figure.

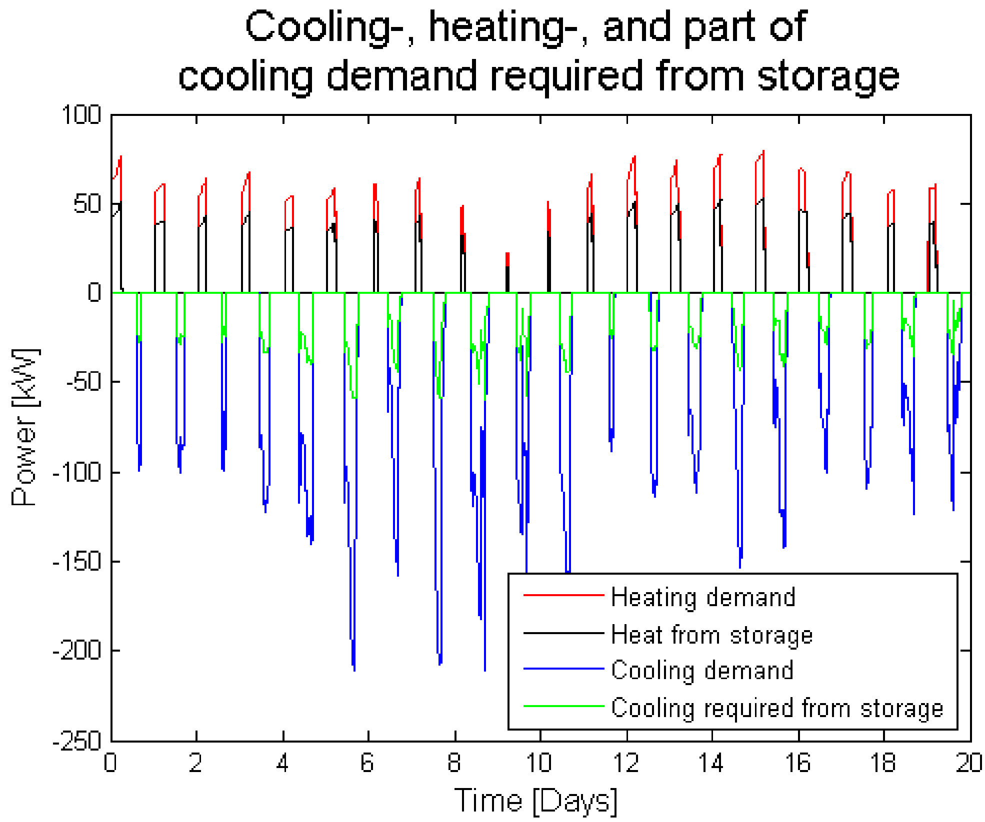


Figure 7.15 The diagram shows the power needed for heating (red marked and above zero) and the power needed for cooling (blue marked and below zero). It also shows the part of the heat power required from the ground (black marked above zero) and the part of the cooling power required from the ground (green marked below zero). The area under the green line and above the black line is equal, which means that the requirements of entered and released energy of the storage are equal. (Day 0= Day 100 of the year, i.e. in mid April)

By summing the energy for cooling and energy these values of modified demands can be calculated.

Heating: 4800 kWh which is 100% of heating demand (includes HP electricity)

Cooling: -3200 kWh which is 28% of cooling demand

If the energies is calculated to energy use per square meter floor area over the year due to climate control the demand is:

Heating: 6.0 kWh/(m^2,year)

Cooling: -4.0 kWh/(m^2,year)

The sum of the energies required from the storage is shown in Figure 7.16. It is only energy released from the ground that is shown; i.e. the electricity in the heat pump is not included in this diagram. The heating demand from the ground is bigger the first days, when the curve is positive. After about 4 days the cooling demand from the ground is bigger, the curve is negative. In the middle of the period, the heating demand gets bigger again. Over the whole period of these 20 days the cooling requirement is as big as the heating requirement.

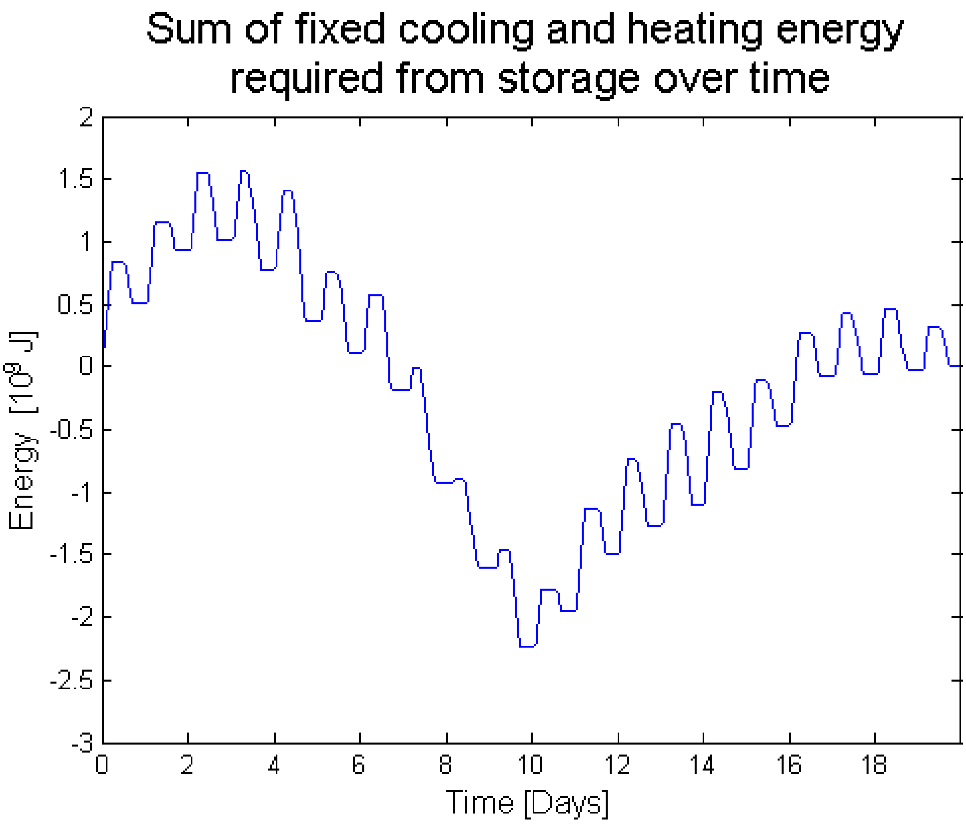


Figure 7.16 Sum of the modified cooling and heating demand over the period. This are the demands required from the storage. Since the curve ends at zero the cooling requirement is as big as the heating requirement over the period. (Day 0= Day 100 of the year, i.e. in mid April)

7.2.3 Design of the energy storage according to the modified demands for climate control

To decide the size of the storage the limitation is that the storage should manage to cover the power and the amount of energy according to the fixed demands for the characteristic period. The storage should manage this without using additional heat. The length of the pipes will be 400m, due to reasonable pressure loss in the system. The surface temperature is 8°C.

7.2.3.1 Too few pipes

In Figure 7.17 the result from a calculation with too few pipes is shown. The gray coloured part in the diagram is the total demand of heating and cooling. No gray part is seen on the heating side, above zero, since the fixed heating demand covers the total heating demand. The sum of the coloured parts is the demand when the heating and cooling are equal, which means the part that is required from the storage. The green part in the diagram is additional energy. The additional energy is used in both for heating and cooling. Why there is an additional part is because the storage is not big enough to manage the demand. The size of the storage used in the calculation is:

Length of pipe: 400m
Number of pipes: 3

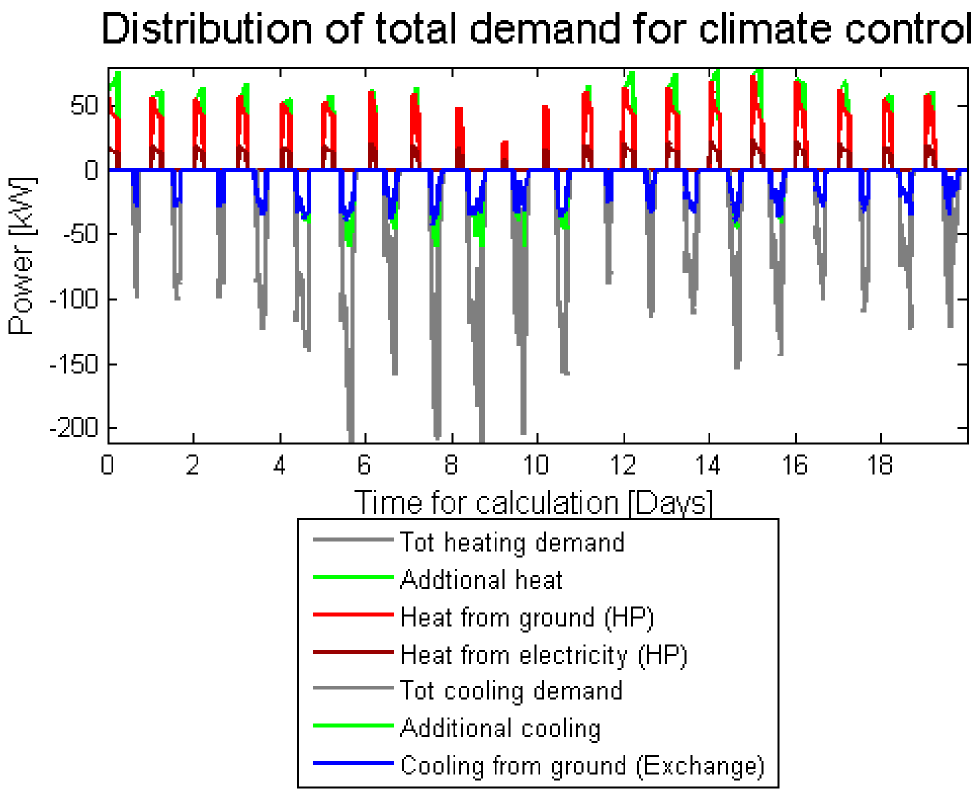


Figure 7.17 The diagram shows the power part of the cooling and heating powers that can be covered by the heat storage. The gray part is the total cooling demand but it is only a part of this required from the storage. The part of the cooling demand that can be covered by the storage is the blue part. The green part is additional energy that is needed to manage the requirement of the storage. On the heating side the gray coloured total heating demand can´t be seen because all the energy for heating is required from the storage. The red part is heat energy from storage and heat pump and the green part is additional energy needed for heating. (Day 0= Day 100 of the year, i.e. in mid April)

With too few pipes only a part of the modified demand can be satisfied. The part of energy that is covered of the storage on cooling and on heating side is:

80 % of modified heating energy demand

92 % of modified cooling energy demand

The part of energy that can be covered by the ground for the total heating demand over this period is:

80 % of total heating demand

26 % of total cooling demand

It can also be seen in Figure 7.18 that the energy entering ground over this period is not zero. More energy is entering the ground over time than released from the ground.

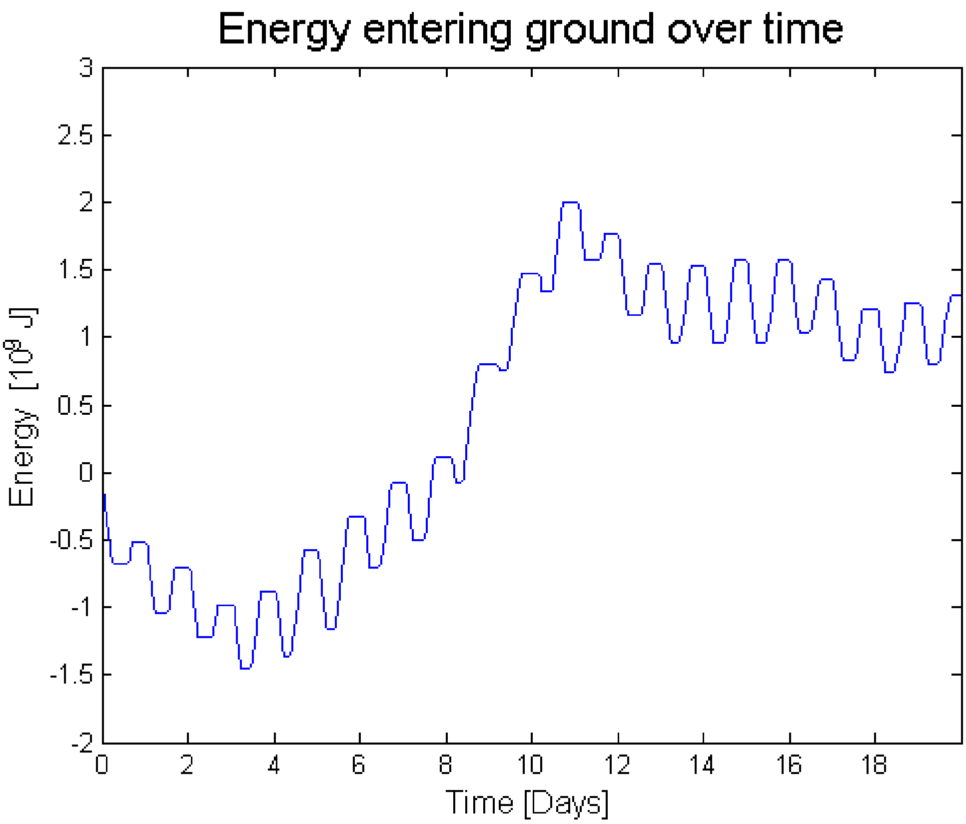


Figure 7.18 Sum of the energy that is entering and released from the ground over the period. Since the curve ends above zero there is more energy entering the ground than released from the ground. (Day 0= Day 100 of the year, i.e. in mid April)

7.2.3.2 Enough with pipes

The system is big enough if having the system size:

Length of pipe: 400m
Number of pipes: 6

It can be seen in Figure 7.19 that no additional energy is needed, no green part is shown. That means the size of the storage is big enough.

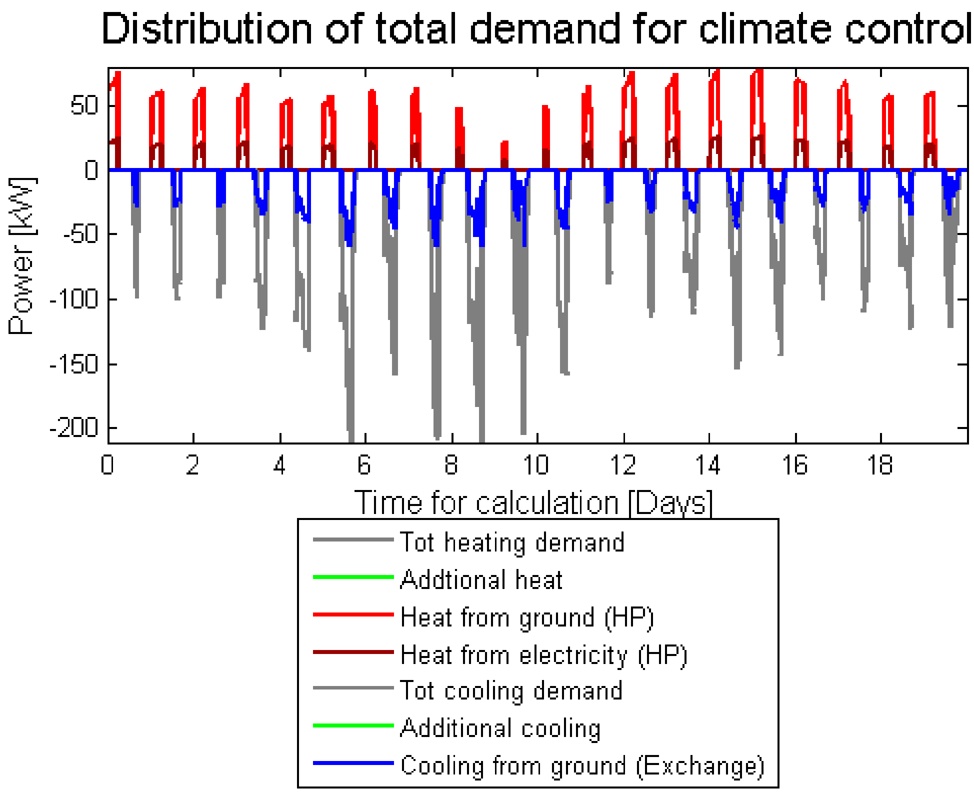


Figure 7.19 The diagram shows the power part of the cooling and heating powers that can be covered by the heat storage. The gray part is the total cooling demand but it is only a part of this required from the storage. All this energy can be covered by the storage and therefore no green part of additional heat is shown. (Day 0= Day 100 of the year, i.e. in mid April)

With enough number of pipes the whole modified demand is satisfied. That means:

100 % of modified heating demand

100 % of modified cooling demand

The part of energy that can be covered by the ground of the total energy demand for heating demand over this period is:

100 % of total heating demand

28 % of total cooling demand

When the storage system is big enough it can manage to satisfy the modified cooling and heating demand. Therefore these last percentages are equal to the percent modified energy part is of the total energy demand over the characteristic periods. It can therefore be expected that the amount of energy entering the ground is equal to the amount of energy released from the ground over the same period. This is calculated in Figure 7.20 and it can be seen that entering energy is equal to released energy over the time period.

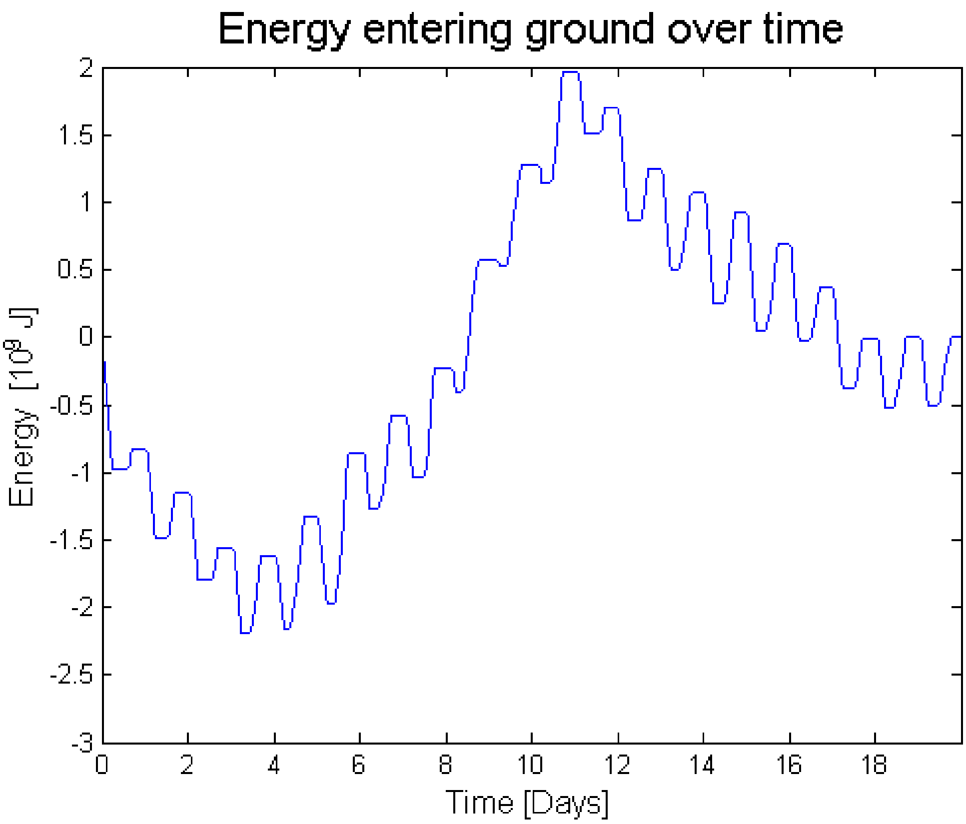


Figure 7.20 Sum of the energy that is entering and released from the ground over the period. Since the curve ends at zero there as much energy entering the ground as released from the ground. (Day 0= Day 100 of the year, i.e. in mid April)

7.2.4 The response in ground and pipe

The long term response of the system is stable since the entering energy is as big as the energy released from the ground. The sum of the energy released from the ground and entering ground over time can be seen in Figure 7.21 were the period with the 20 characteristic days has been repeated.

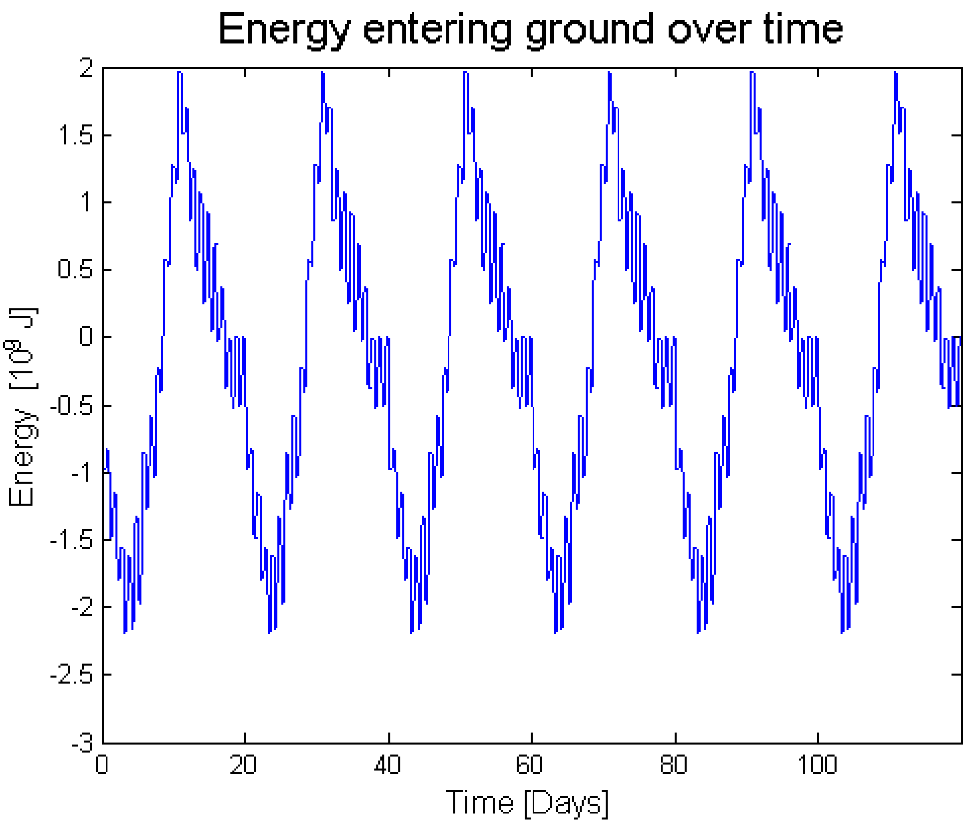


Figure 7.21 Sum of the energy that is entering and released from the ground over the repeated period of the 20 characteristic days. Since the curve ends at zero there as much energy entering the ground as released from the ground. (Day 0= Start day of the period with the 20 characteristic days)

It can also be of interest to know the volume of the ground that is used for energy storage. In Figure 7.22 the temperature distribution in ground over the repeated period of 120 days can be seen. The figure is calculated for segment in the middle of the pipe. On the x-axis the radius out from the pipe is shown. It can be seen that about 0.8 to 1 meter of the ground around the pipe is affected by the temperature in the pipe and that volume is used for thermal energy storage.

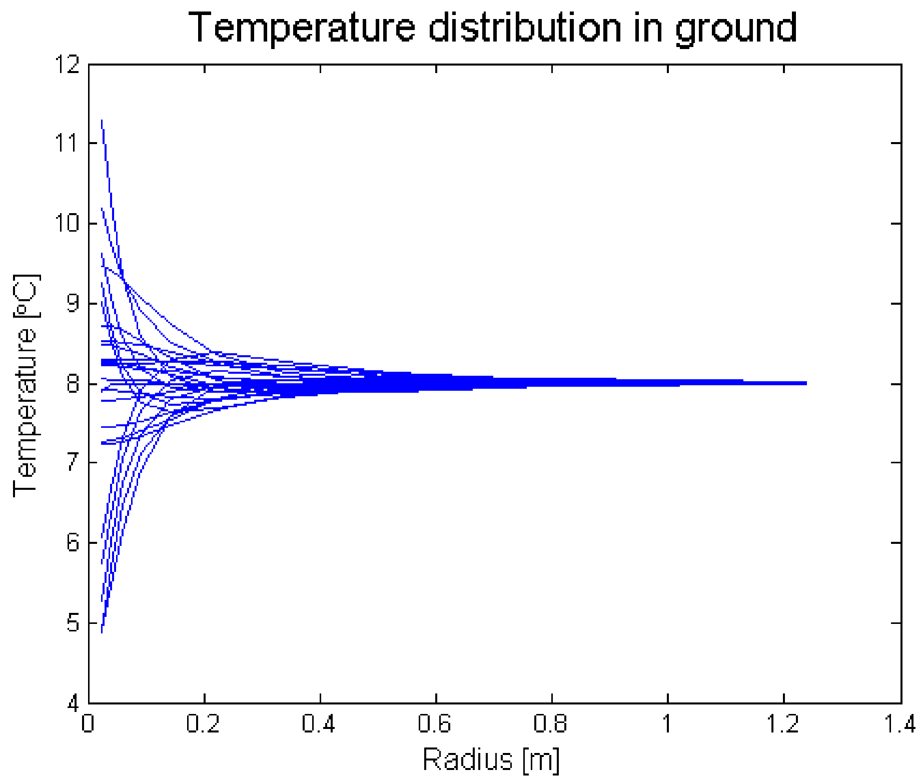


Figure 7.22 The temperature in the ground around the pipe at different radius from centre of the pipe.

The temperature distribution in the pipe is shown in Figure 7.23.

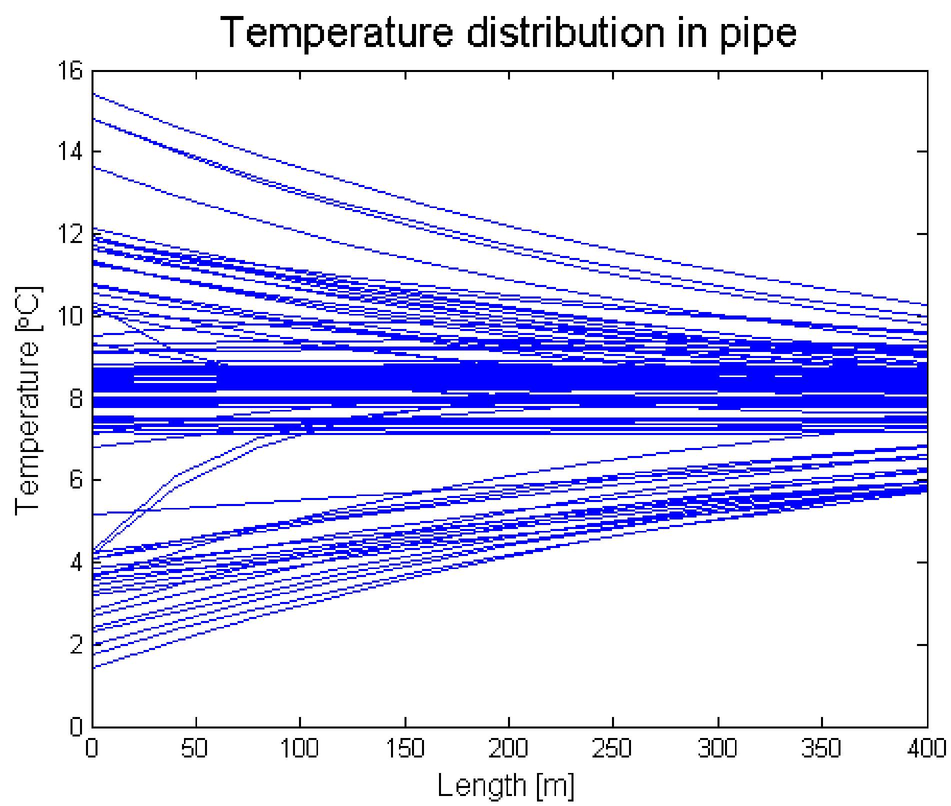


Figure 7.23 Temperature distribution over length of the pipe (Length 0= Inlet, Length 400=outlet)

The inlet and outlet temperature over this period can also be seen in Figure 7.24 were the inlet temperature is shown as a blue part and the outlet temperature is shown as red. If the blue line is above the red line the fluid in the pipe is chilled down in the pipe.

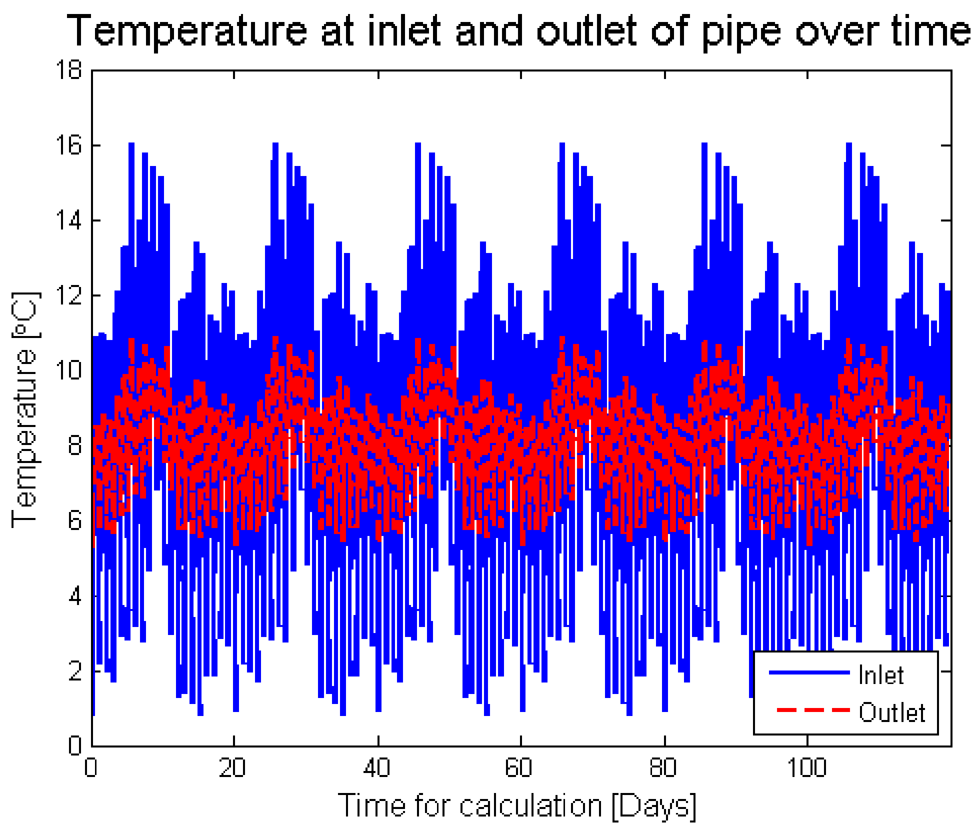


Figure 7.24 The change in temperature from the inlet to the outlet of pipe is shown. It can be seen that the inlet temperature (blue) varies between 16°C and 1°C and the outlet temperature (red) varies between 11°C and 5°C. (Day 0= Start day of the period with the 20 characteristic days)

7.2.5 How to control the use of the storage

In Figure 7.23 the temperature out from the pipe is shown. It can be seen that for this design the outlet temperature will never be bigger than 12°C or lower than 4°C. A practical way to control the system could then be to measure the outlet temperature. If it gets to low or to high the current use of the ground for climate control is turned off, to not overheat or over cool the ground. It is important to remember that the storage is design on a 24-hour basis. Even if energy may be stored during longer or shorter it is not the purpose. The result from a calculation that turns of the system when the outlet fluid reaches a 12°C or 4°C can be seen in Figure 7.25. The calculation is starts when the characteristic days the system is designed for starts at 100 days after New Year. The calculation starts at this time because it reduces the power of using heat due to the initial temperature in the ground.

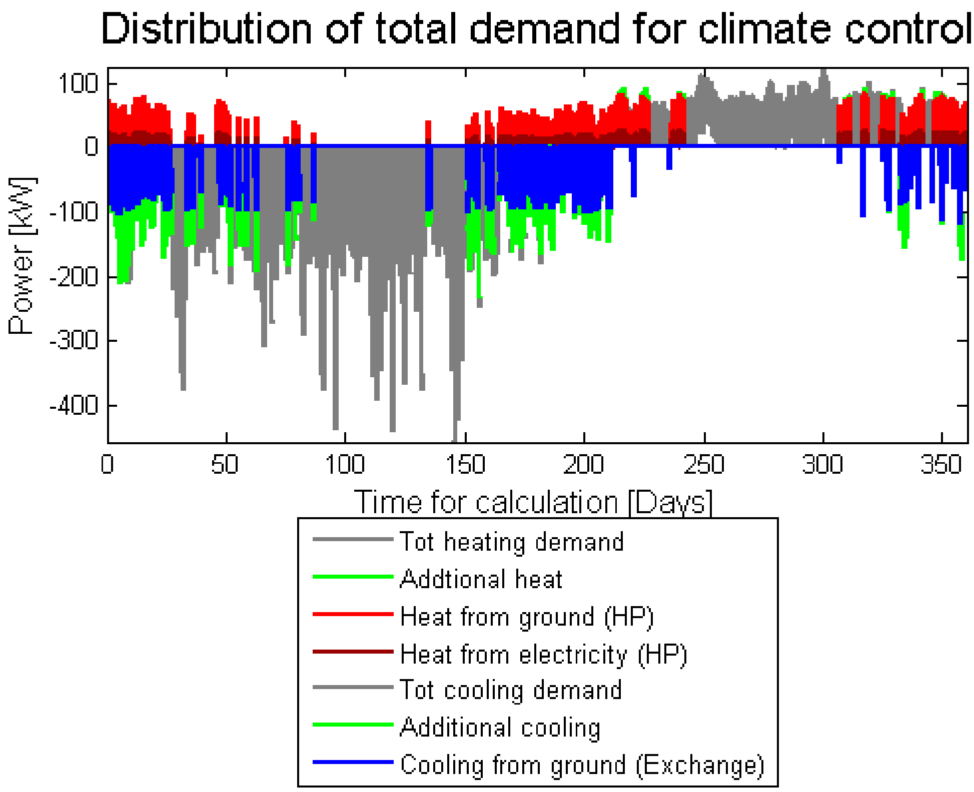


Figure 7.25 Shows when the 24-hour storage can be used due to the control system described. The gray area indicates when the storage system can't be used due to risk of overcooling or overheating. (Day 0= Day 100 of the year, i.e. in mid April)

In Figure 7.25 the ground is used during the period with coloured areas, the gray areas in-between are periods when the heat and the cooling need is covered with another energy source. It can be seen that the ground can't manage the total demand of the heating or cooling power even when it is in use. The periods when storage is not in use due to the outlet temperature of the fluid can be seen in Figure 7.26. If the storage is turned off, it will not be in use again until the mode of the climate unit changes, i.e. mode from heating to cooling or reversed.

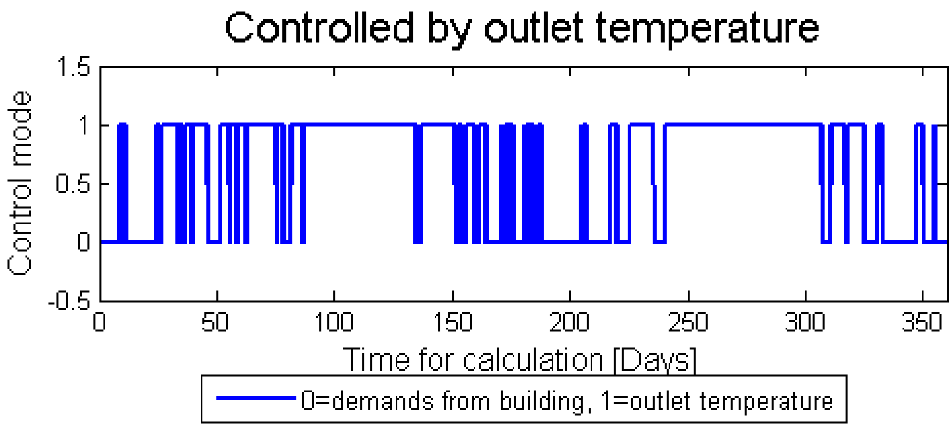


Figure 7.26 When the line is at 1 it means that the storage system is not in use due to the outlet temperature. If the line is at zero the use of the storage system is decided by the heating and cooling demand in the building. (Day 0= Day 100 of the year, i.e. in middle of April)

The heating and cooling demands are not modified in this calculation but since the size of the storage is already designed the powers entering ground is limited due to this. The energy that can be covered by the storage is

34 % of total heating demand for the whole year

17 % of total cooling demand for the whole year

In Figure 7.27 the energy entering and released from the ground can be seen. Even if the demands are not modified it can be seen that the use of the control system, due to outlet temperature, controls the entering energy and released energy from the ground to be almost equal over the year.

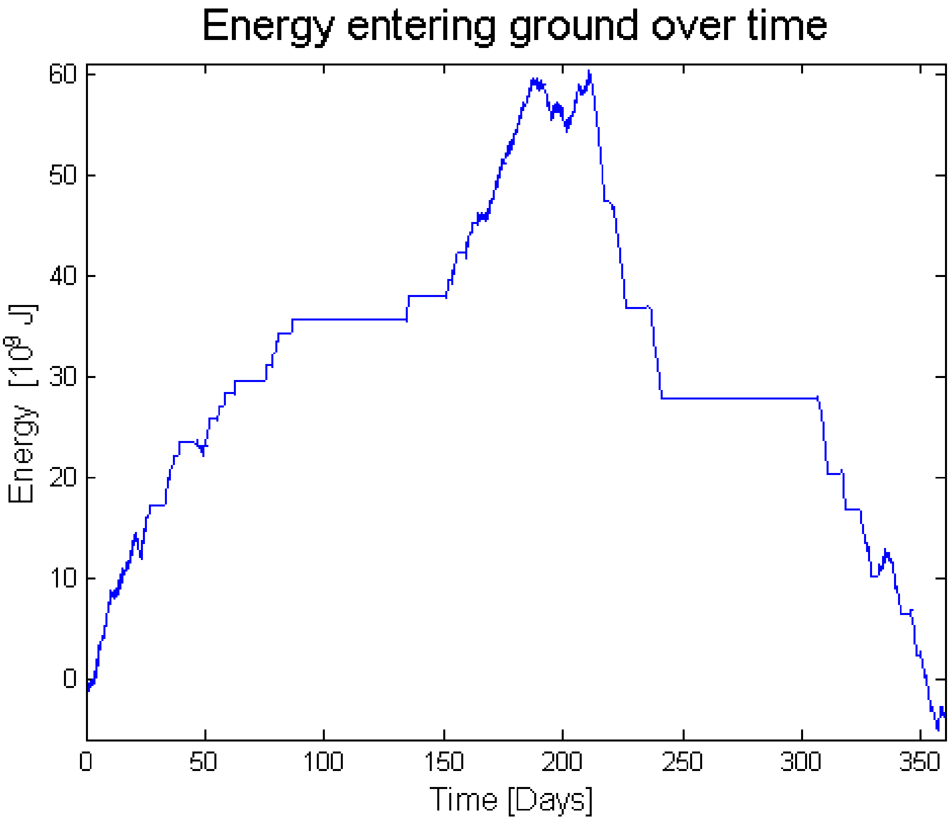


Figure 7.27. The sum of the energy that is entering and released from the ground over the year. Since the curve ends almost at zero, there is approximately as much energy entering the ground as released from the ground. The system is stable. (Day 0= Day 100 of the year, i.e. in mid April)

Thus it is important to notice that the volume of the ground used for storage is bigger for the calculation all over the year. That means the pipes need a bigger distance between each other and the also needs to be placed further down in the ground. The use of bigger volume is due to that the storage also stores energy over the whole periods of spring or autumn. That the heat is to some extent stored over this longer periods can be seen in Figure 7.27 were the sum of entering and released energy is close to zero when summer and winter starts and the underground thermal storage is turned off. The part of the ground that has a noticeable temperature variation is about 1 to 1.5 meter, and can be seen in Figure 7.28.

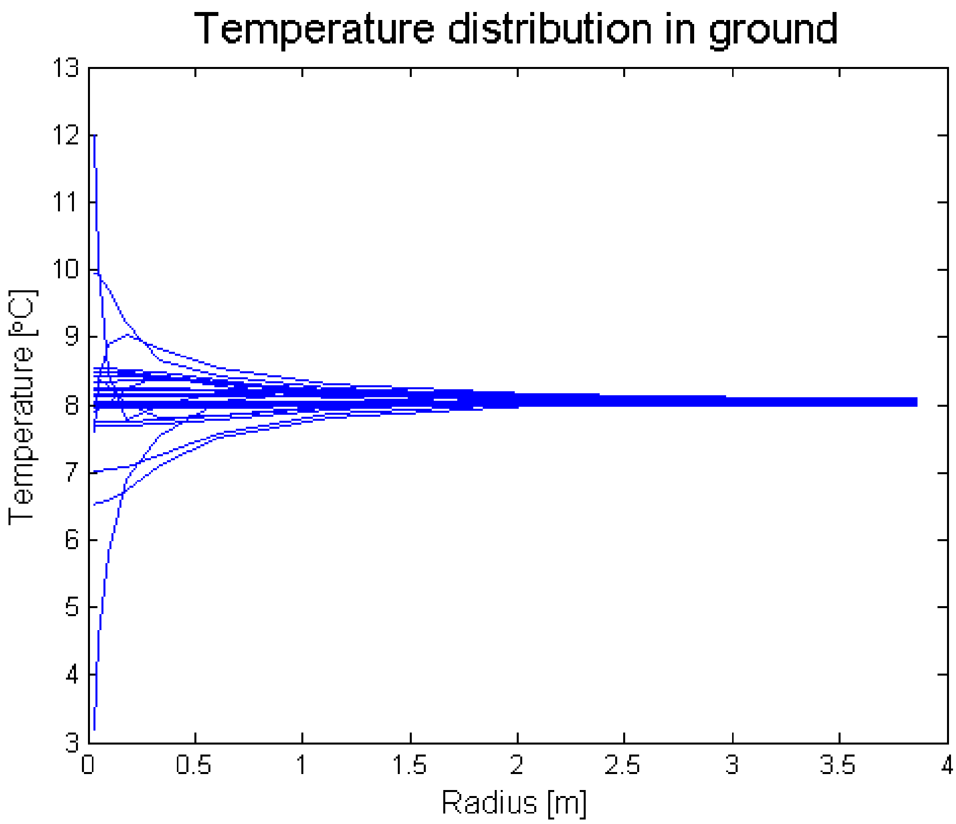


Figure 7.28 The temperature distribution in radial direction perpendicular out from the pipe into the ground at different time step.

7.2.6 How much can the energy storage with 24-hour basis manage of the climate demand over the year

Over the time period with the chosen 20 days the ground storage can manage

100 % of total heating demand for the 20-days

28 % of total cooling demand for the 20-days

But this time period is not representative for the whole year and to see during what time of the year the controlled system is used. From the calculations in chapter the heat storage with the control system can manage

34 % of total heating demand for the whole year (Includes HP energy)

17 % of total cooling demand for the whole year

This means that from the total heating demands, which are:

Total heating demand: 150000 kWh
Total cooling demand: -210000 kWh

Or per square meter

Heating: 10.5 kWh/(m^2,year)
Cooling:-14.8 kWh/(m^2,year)

The heat storage can save

Savings of total heating: 50000 kWh (20000 kWh of this is energy to HP)
Savings of total cooling 36000 kWh

Or expressed in demands per square meter the heat storage can reduce the demands per square meter to:

Heating after storage: 7.0 kWh/(m^2,year) (1.2 kWh/(m^2,year) extra to HP)
Cooling after storage: -12.3 kWh/(m^2,year)

7.3 Demands and design of 1-hour storage

To compare the storage on a 24-hour basis with storage on a 1-year basis the simulation on a 1-year basis storage is made in this chapter. At first the demand over the year is modified so the heating and cooling requirement of the storage is equal. Afterwards, the design of the storage is made to find the number of pipes needed. In the end the temperature response in the ground is presented.

7.3.1 Modified climate control demands over the year

The cooling and heating demand over the year is discussed in Chapter 7.1 and the energy demand for cooling is bigger than the energy demand for heating over the year. To be able to design a heat storage that is not overcooled or overheated the demands for the climate control is modified. That means some percent is taken away from the cooling to make it equal to the heating demand. The part taken away needs to be fulfilled with another system. In Figure 7.29 it is the black and the green part of the cooling and heating demand that is required from the storage. The rest of the heating demand is covered by the extra heat pump energy and the rest of the cooling demand needs to be covered with another system. The black part is as big as the green part so the energy entering ground will be equal to the energy released from the ground.

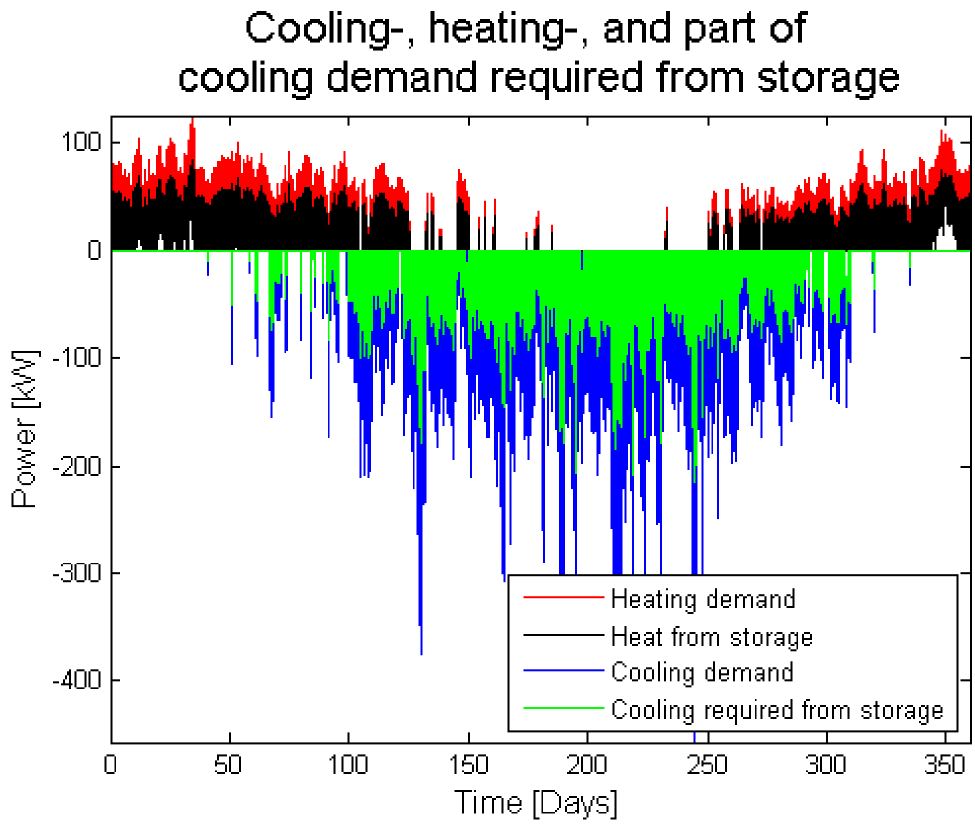


Figure 7.29 The diagram shows the power needed for heating (red marked and above zero) and the power needed for cooling (blue marked and below zero). It also shows

the heat power part required from the ground (black marked above zero) and cooling power required from the ground (green marked below zero). The area under the green line and above the black line is equal, which means that the requirements of intake and outtake of energy of the storage is equal. (Day 0= 1 of January)

In Figure 7.30 it can be seen that the modified demands requires as much heat energy from the storage as cooling energy.

Total heating demand: 150000 kWh which is 100% of heating demand (includes HP electricity)

Total cooling demand: -100000 kWh which is 47% of cooling demand

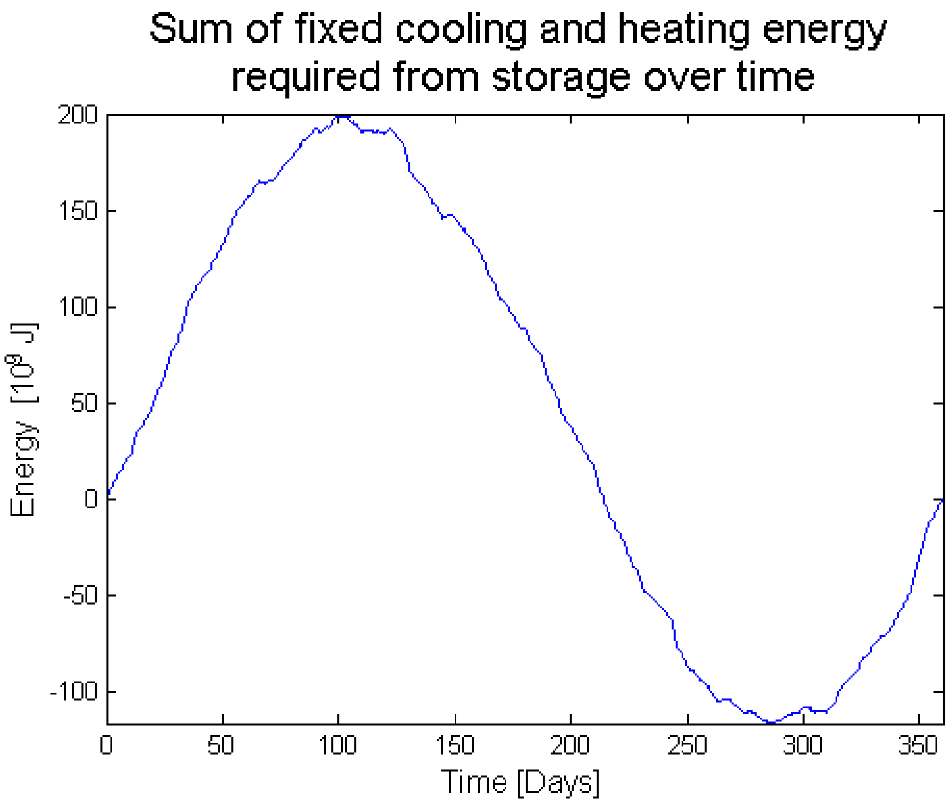


Figure 7.30 Sum of the modified cooling and heating demand over the year. This are the demands required from the storage. Since the curve ends at zero the cooling requirement is as big as the heating requirement over the period. (Day 0= 1 of January)

7.3.2 Design of the energy storage according to the modified demands for climate control

Due to that the peaks of cooling and heating are big even after the modification of the demands the size of the storage will be chosen so it can manage the most of the modified demands but the highest peaks are ignored. The surface temperature is 8°C. The size of the system used in the calculation is:

Length of pipe: 400m
Number of pipes: 8

Only 2 pipes more is used than for the system designed for 24-hour basis. The result from how much the storage can manage of the modified demands can be seen in Figure 7.31. Were the green parts is parts where additional power is needed to cover the heating and cooling demand up to the modified demand.

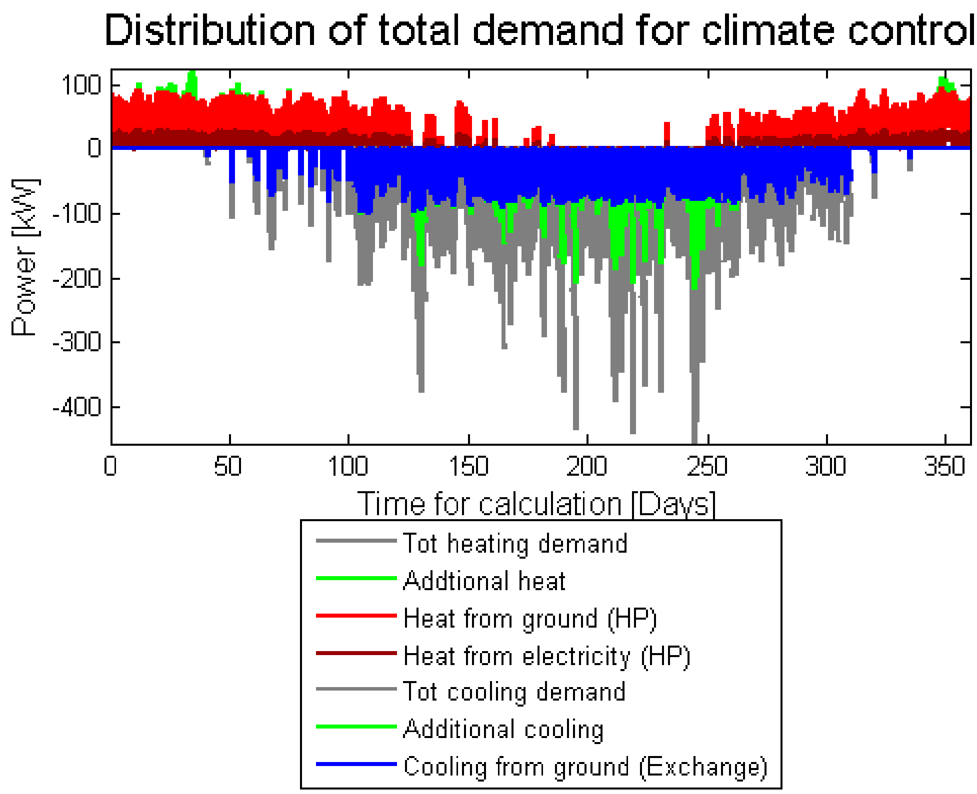


Figure 7.31 The diagram shows the power part of the cooling and heating powers that can be covered by the heat storage. The gray part is the total cooling demand but it is only a part of this that can be covered by the storage. The part of the cooling demand that can be covered by the storage is the blue part. The green part is additional energy that is needed because the storage can't manage the requirement of the storage. On the heating side the gray coloured total heating demand can´t be seen because all the energy for heating is required from the storage. The red part is heat energy from storage and heat pump and the green part is additional energy needed for heating. (Day 0= 1 of January)

Of the modified heating demand the storage in this situation can manage

97 % of modified heating demand

89 % of modified cooling demand

That means of the total demand of cooling and heating

97 % of total heating demand

42 % of total cooling demand

In Figure 7.32 the sum of the energy entering ground and released from the ground can be seen. The requirement of cooling and heating are close to equal even if not designing the system for the peaks in modified demands.

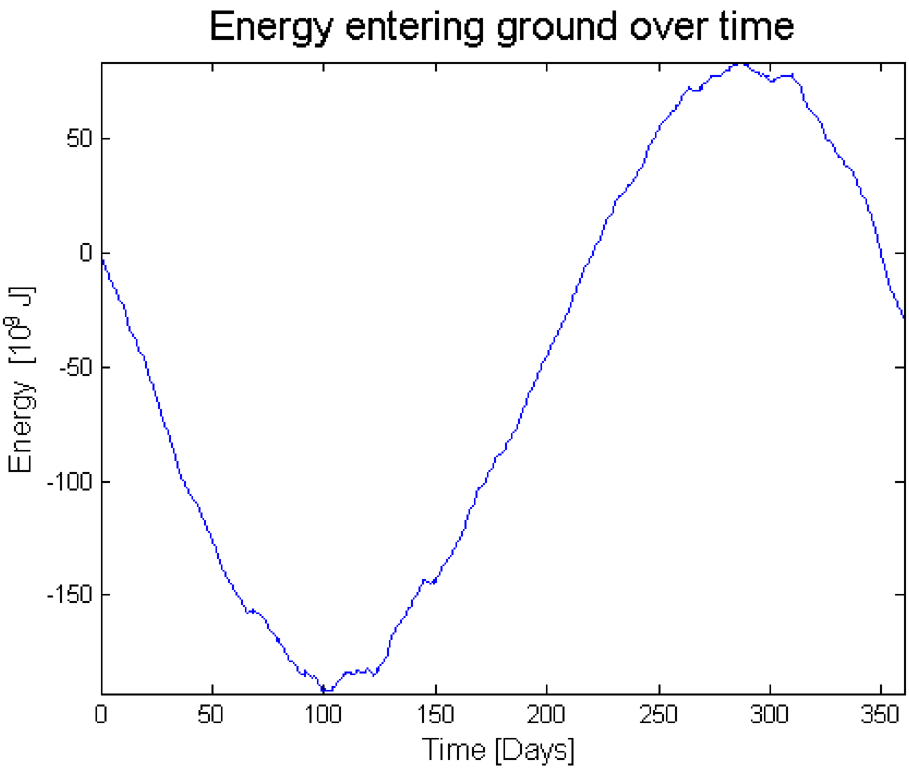


Figure 7.32 Sum of the energy that is entering and released from the ground over the period. Since the curve ends below zero there is slightly less energy entering the ground than is released from the ground. (Day 0= 1 of January)

7.3.3 The response in ground and pipe

For the storage used all over the year each pipe need more space compared with the 24-hour basis system. It can be seen in Figure 7.33 that about 4 meters around the pipe is influenced by the temperature variation in the pipe.

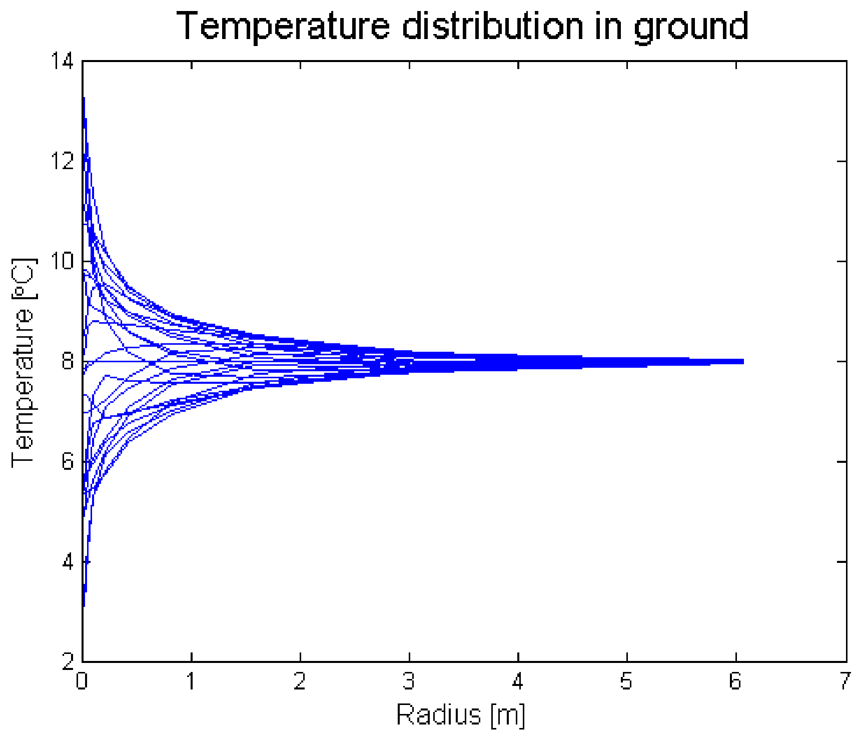


Figure 7.33 The temperature distribution in radial direction perpendicular out from the pipe into the ground at different time step.

The temperature in the pipes is also varying more for the use of a 1-year storage, this can be seen in Figure 7.34.

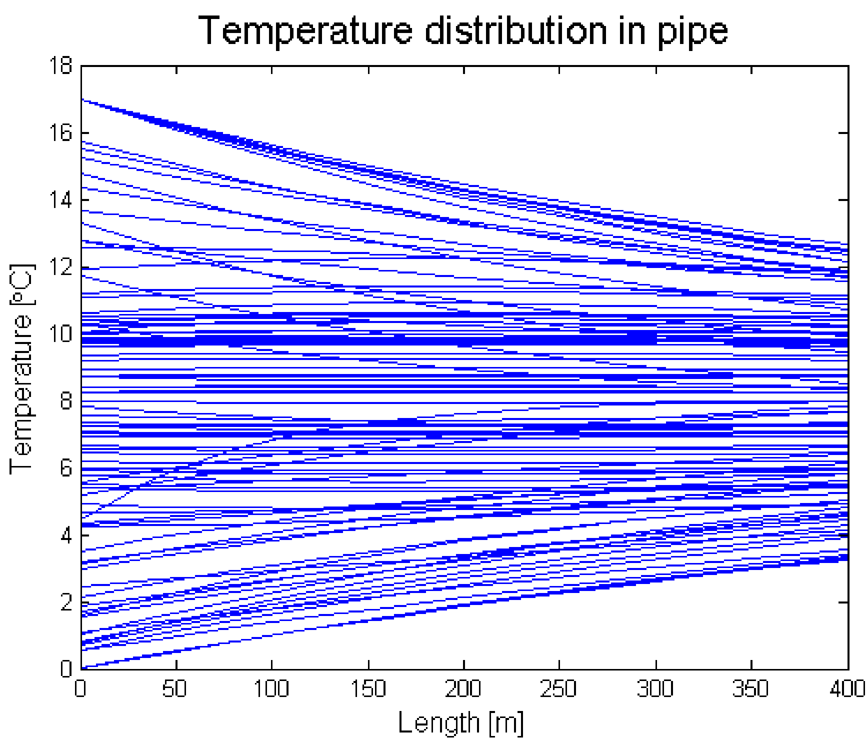


Figure 7.34 The temperature distribution in of the fluid in the pipe at different time step.

In Figure 7.35 it can also be seen that the variation in pipe temperature is depending on the time of the year.

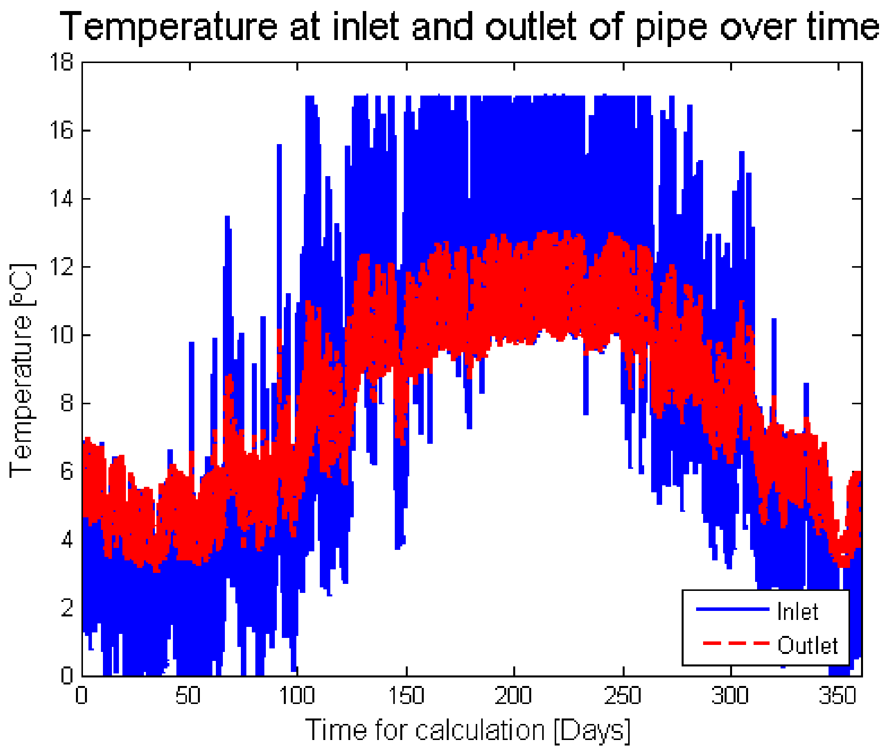


Figure 7.35 The change in temperature from the inlet to the outlet of pipe is shown. It can be seen that the mean value of the temperature at the inlet (blue) and outlet (red) varies due to the season. . (Day 0= 1 of January)

7.3.4 How to control the 1 year-basis system

It would not be possible to control this system as for the 24-hour basis since the energy storage is in use all the time. The problem with overcooling or over heating is for the year-basis only if too much heat is energy the ground during cooling. Since the pipes have a certain length there is a limit in the power that can enter the ground. The result for calculating for the whole year without using any control system, but only the length of the pipe limiting the energy entering the ground during cooling mode can be seen in Figure 7.36.

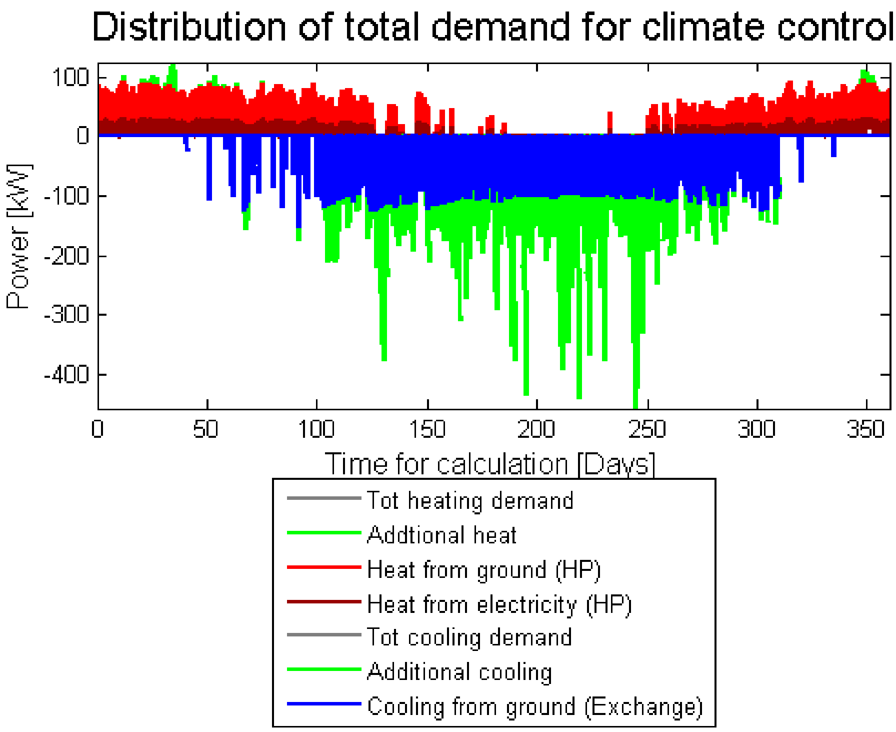


Figure 7.36 The diagram shows the power part of the cooling and heating power that can be covered by the heat storage. The part of the cooling demand that can be covered by the storage is the blue part. The green part is additional energy that is needed because the storage can't manage the demand from the building. On the heating side the red part is heat energy from storage and heat pump and the green part is additional energy needed for heating. (Day 0= 1 of January)

In Figure 7.37 it can be seen that more energy is entering the ground over the whole year. That means there is a need for a controlling system hinders the system to enter more energy to the system than is released from the system.

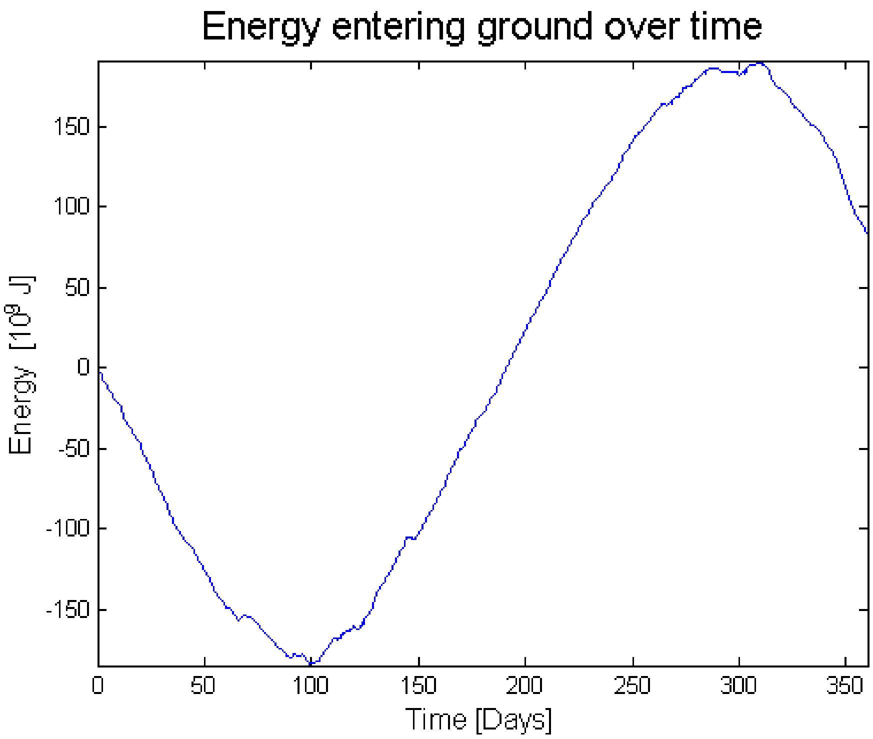


Figure 7.37 Sum of the energy that is entering and released from the ground over the period. Since the curve ends above zero there is more energy entering the ground than is released from the ground. (Day 0= 1 of January)

If calculation the heat and cooling demand that can be covered by the storage even if the sum of the cooling and heating demand entering or released from the storage is equal the energy that can be saved is.

97 % of total heating demand
57 % of total cooling demand

7.3.5 How much can the energy storage manage of the demand over the year

The heat storage can save

97 % of total heating demand (includes HP energy)
57 % of total cooling demand

The total heating demands for the year are:

Total heating demand: 150000 kWh/year
Total cooling demand: - 210000 kWh/year

Or per square meter

Heating: 10.5 kWh/(m^2,year)
Cooling:-14.8 kWh/(m^2,year)

If no control system is used the heat storage can save the percentage of saving from chapter is used. That means the heat storage can save:

Savings of total heating: 140000 kWh/year (49000 kWh/year of this is energy to HP)
Savings of total cooling 120000 kWh/year

Or expressed in demands per square meter the heat storage can reduce the demands per square meter to:

Heating after storage: 0.4 kWh/(m^2,year) (3.3 kWh/(m^2,year) extra to HP)
Cooling after storage:-6.4 kWh/(m^2,year)

7.4 Influence of surface temperature calculated for the 20 characteristic days.

The surface temperature affects the function of the heat storage. In this chapter the behaviour of the ground and pipe temperatures due to the surface temperature is described. This chapter does not have influence of the design of the system. Only some results that highlights that it may be important to take the influence of the surface temperature into account are described here. The calculations in this chapter are made for the modified demands of the characteristic 20-days period.

7.4.1 Surface temperature of 15 degrees

For saving place it may be of interest to put the pipe system under a building. The size of system used in the calculation is the one designed for the 24-hour basis storage

Length of pipe: 400m
Number of pipes: 6

The system is placed 2 meters under the ground surface and a 0.2 m thick insulation layer is placed on top of this. If the pipe is located under basement that has a temperature of 15 degrees the ground will be heated. In Figure 7.38 it can be seen that the possibility to use the ground for cooling decreases. That is shown by that the green part of additional cooling increases.

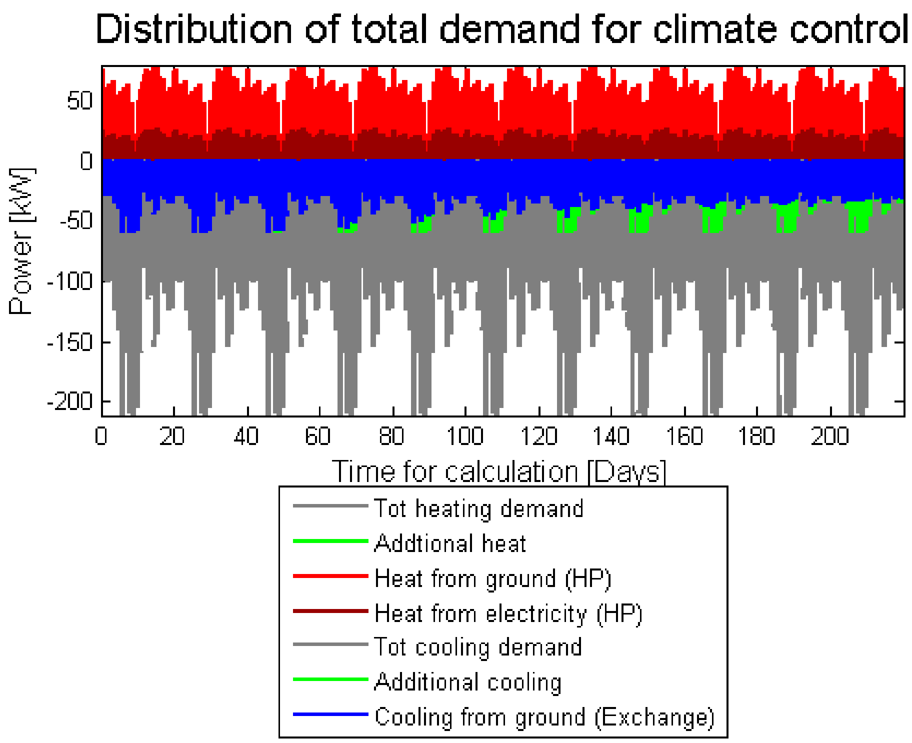


Figure 7.38 The diagram shows the power part of the cooling and heating powers that can be covered by the heat storage. The gray part is the total cooling demand but

it is only a part of this required from the storage. The part of the required cooling demand that can be covered by the storage is the blue part. The green part is additional energy that is needed to manage the required demands of the storage. It can be seen that the green area increases when the time goes on. (Day 0= Start day of the period with the 20 characteristic days)

The decrease in the possibility to use the ground is due to that the fluid can't release as much heat to the ground as the ground gets warmer due to the temperature in the basement. The fluid in the pipe can't be cooled enough. The inlet and outlet temperature of the fluid in the pipe can be seen in Figure 7.39.

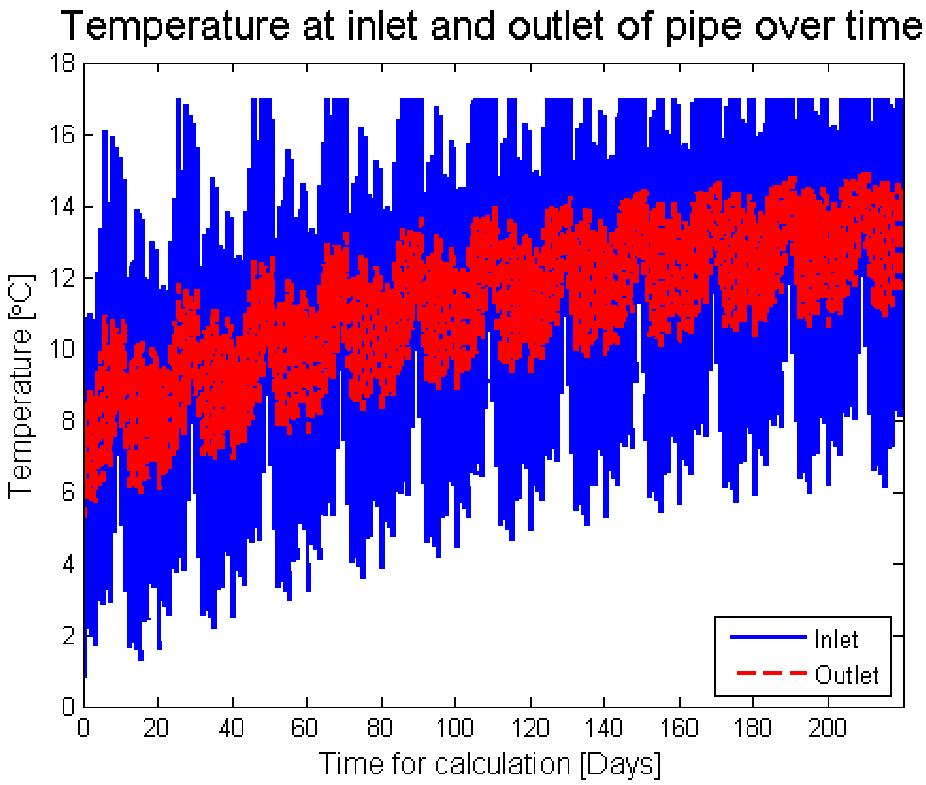


Figure 7.397.40 The change in temperature from the inlet to the outlet of pipe is shown. It can be seen that the mean value of the inlet temperature (blue) and outlet temperature (red) increases over the time. This is due to that the ground is heated by the temperature at the surface. (Day 0= Start day of the period with the 20 characteristic days) (Day 0= Start day of the period with the 20 characteristic days)

In Figure 7.41 it can also be seen that the energy that enters the ground decreases all the time. Therefore the curve of the sum of the energy entering ground is bending downwards. Not as much energy can enter the ground as taken out from the ground. The system is not stable.

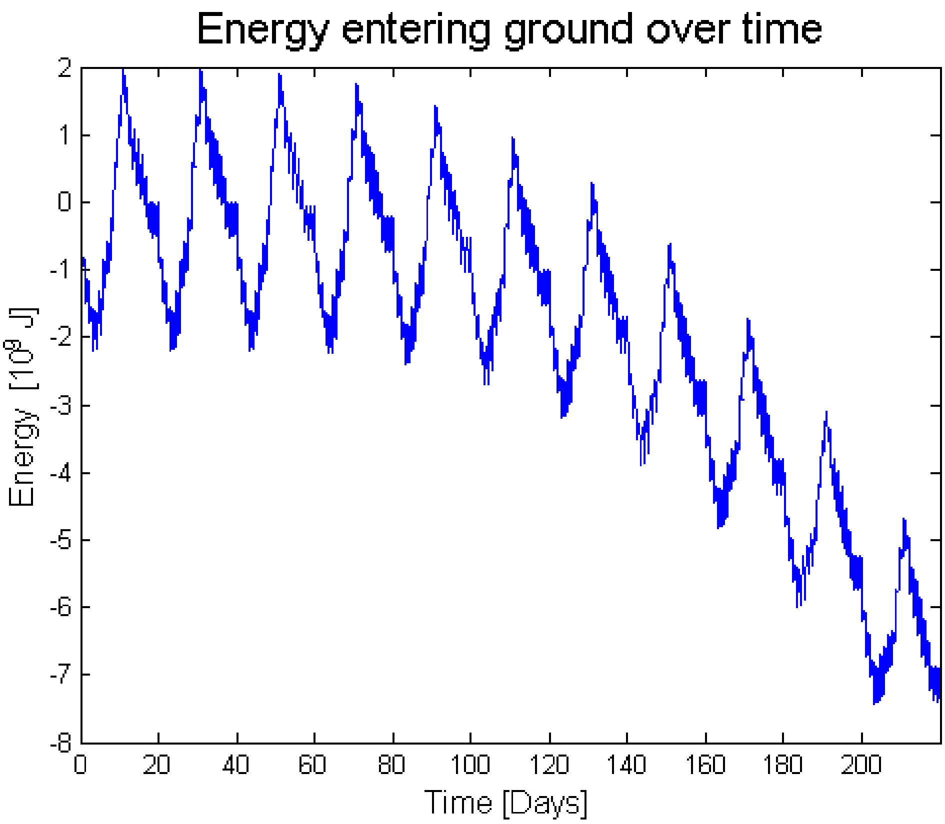


Figure 7.41 Sum of the energy that is entering and released from the ground over the period. Since the curve is bending downwards less and less energy can enter the ground over the time. (Day 0= Start day of the period with the 20 characteristic days)

If the calculation is started at a ground temperature that has been heated by the ground the ground temperature is 15°C. This temperature may not be totally correct due to that some energy from the house is transported away before it reaches the pipes. But the calculation will be on the safe side. If the system should manage a temperature of 15°C at the surface it needs about 20 pipes of 400 meters to use only a small amount of additional energy for the cooling. For the surface temperature of 15°C a small part of additional energy has to be used all the time. This is because the temperature demand of the fluid entering the cooling system in the building is 14°C, which is lower than 15°C.

The depth of where the pipes are placed is also of importance for knowing if the surface temperature affects the ground temperature at the depth of where the pipes are placed. But this calculation if out of the limitation of the program due to that the heat transport between pipes and surface is only one dimensional in the mathematical model. If the building and the pipes are located vertically beneath each other but far away from each other the heat from the surface will not affect the pipes. This is because the transport of energy from the basement rather goes to the surfaces around the building.

7.4.2 Surface temperature of 12 degrees

For the a case with a higher surface temperature of 12°C it is theoretically possible for the system to manage both the cooling and heating demand. In the calculation the size of the system increased with another 3 pipes, to manage the demand. I.e., the size of the system is

Length of pipe: 400m
Number of pipes: 9

The distance to the surface is still 2 meter and the insulation layer is still 0.2 m thick. For this situation the system can manage a basement temperature of 12 degrees. This can be seen in Figure 7.42 were no additional cooling is needed as for the 15 degrees in basement.

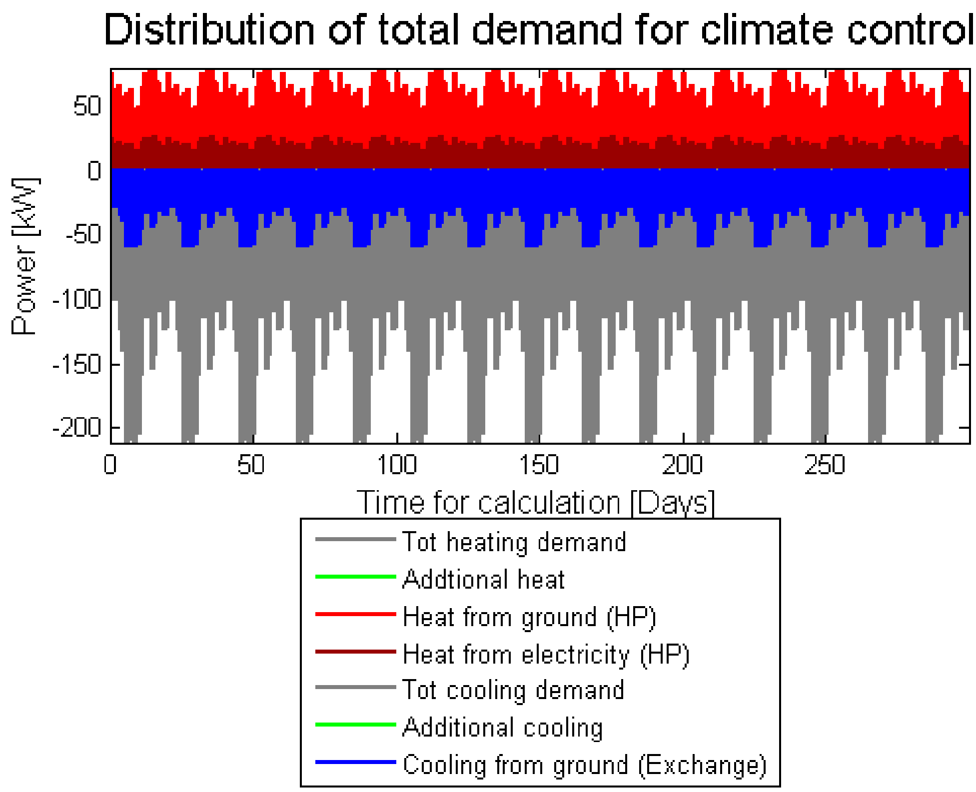


Figure 7.42 The diagram shows the power part of the cooling and heating powers that can be covered by the heat storage. The gray part is the total cooling demand but it is only a part of this required from the storage. The part of the required cooling demand that can be covered by the storage is the blue part. There is no green part that indicates a need of additional energy for this system and the surface temperature of 12°C. The system can manage the requirements. (Day 0= Start day of the period with the 20 characteristic days)

The increase of ground temperature due to the temperature in the basement does matter when the building needs cooling. It matters in cooling mode because of the demands of the temperature in the cooling system in the building, which is 14/17C. In the heating mode there is no demand of a certain ground temperature due to the heat pump. This is correct if neglecting changes of COP within the possible temperature variation of the ground. If the ground is heated due to the basement temperature the driving forces to chill down the fluid temperature in the pipe decreases. If the system should manage to cool the fluid the total length of the pipes needs to increase. The inlet and outlet temperature can be seen in Figure 7.43. In the calculation it can be seen that the temperatures in the end of the calculation almost reached a steady state value.

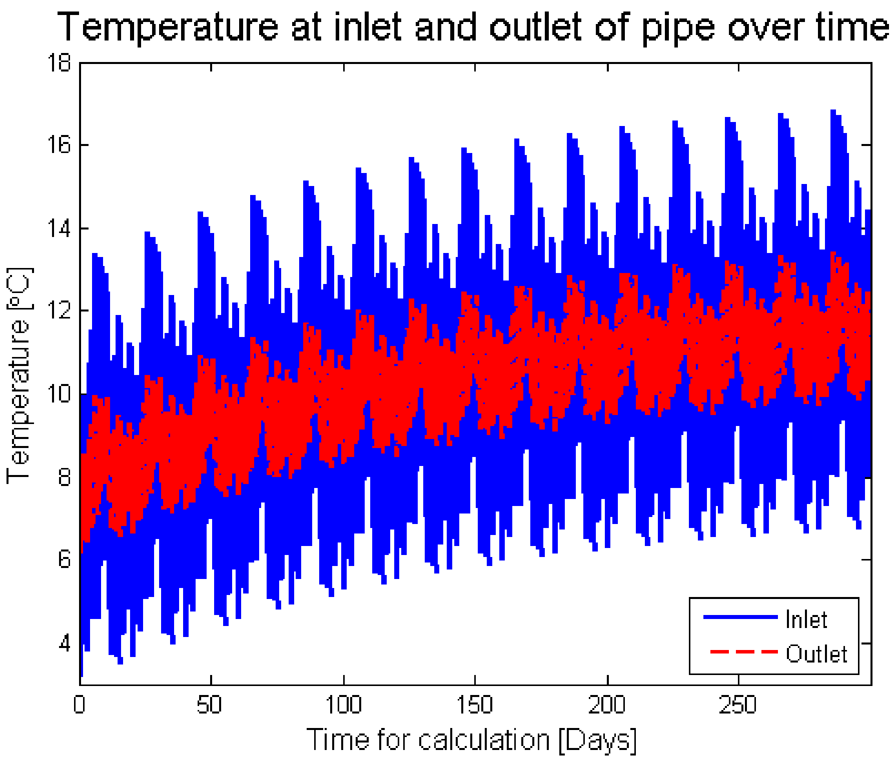


Figure 7.43 The change in temperature from the inlet to the outlet of pipe is shown. It can be seen that the mean value of the inlet temperature (blue) and outlet temperature (red) increases over the time but it has almost reached a stable value in the end of the calculation period. (Day 0= Start day of the period with the 20 characteristic days)

In Figure 7.44 the long term response is seen. For the calculation as much energy is entering the ground as leaving the ground all over the calculation time. That insures long term function of the system.

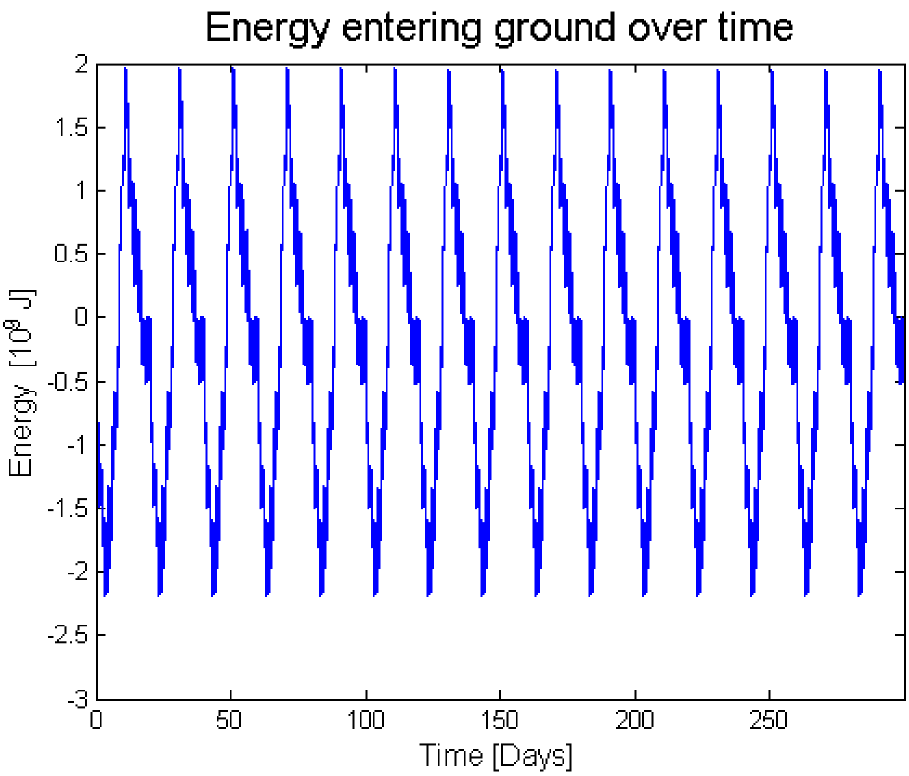


Figure 7.44 Sum of the energy that is entering and released from the ground over the period. Since the curve ends at zero as much energy is entering the ground as released from the ground. The system is stable. (Day 0= Start day of the period with the 20 characteristic days)

8 Discussion

The results from the calculations are discussed in this chapter. First the use of the 24-hour storage is discussed together with a discussion of the demands of the building. Afterwards the storage on a 24-hour basis is compared with using storage on a seasonal basis. This comparison is made both due to energy, power and use of space for the pipes and length of the pipes. In the end there is a discussion about how the surface temperature can influence on the function of the heat and cold storage performance.

8.1 When can the 24-hour basis storage be used due to demands from building

In Chapter 7.1 the result from the heating and cooling demand over the year is shown. It can be noticed that the demands from the building gives a change between heating- and cooling mode over days during spring and autumn. This means that the 24-hour storage only can be in use that part of the year.

The time the period of heating and cooling behavior is changing over the 24-hour basis does also depend on the building and on requirements for the climate in the building. For example, if a wider temperature range is allowed in the building, the period of heating during days and cooling during nights shortens. The variation between heating and cooling does also depend on the loads in the building, with high changes of internal loads during day and night this behavior gets more distinct.

The amount of heat capacity in the building does also affect the use of heat/cold storage. If having a high heat capacity, the saving with heat storage over the day decreases since the material in the house can store the energy and dampens the temperature rise on the indoor air. Therefore if the building has high heat capacity, the indoor air can take higher internal loads and or internal loads during a longer time without need for cooling if having high heat capacity in the building. It also takes more loss of energy from the building before the indoor temperature fall as much as a building with less heat capacity. With high heat capacity in the building it may therefore be less beneficial to use heat and cold storage and with low heat capacity in the house the heat and cold storage may be more useful.

If doubling the internal loads the period with heating during nights and cooling during days becomes longer. It is just a time in the middle of the summer that only needs cooling. If the heat load in a building is extra high during daytime it could be more useful, than for normal internal loads during daytime, to have energy storage over 24-hour basis since there is an excess of heat produced many days of the year. This excess can be stored and released to the indoor air the night after. Compared with 24-hour basis storage it could be less beneficial to store energy over season for the case with doubled internal loads. This is due the heating and cooling demand that is more spread out. There is no constant heating need during winter, as with normal internal loads. The situation with doubled internal loads in the building is not more investigated in this thesis since it is not an expected scenario of the building. But for other buildings that produce a lot of internal heat during days, the 24-hour storage could be a god solution for lowering the energy demand.

Another aspect that is not taken care of in this report is different heat loads in different rooms. For example a server room with a lot of machines and a need for cooling all year around. The limited areas with extra heat production gives energy that can be stored in the ground and released when other parts of the building needs heat. But even if some areas have such an internal heat production that requires cooling even during winter, there is often another room that needs heating at the same time. To go the detour around the heat storage is then unnecessary; it is probably more preferable to use the heat energy immediately.

If the sun is neglected as an internal load, as if sunshades are used, the demand for climate control of the building changes. The cooling energy demand decreases and there is a need of heat energy even in summer. The period of heating and cooling does visually look as long as the period for the original situation in the building, when sun is included, but the period starts closer to the summer. This can be seen when comparing Figure 7.1 and Figure 7.10. If this situation is favorable for using energy storage over 24-hour basis is not investigated more in this thesis but the sum of the cooling and the sum of the heating demand are more equal over the period without the sun as an internal load. Because of this it could be expected that a bigger part of the cooling demand can be stored. But since less total cooling energy is used in the situation with neglected heat from the sun the absolute saving may be less than for the original situation.

8.2 24-hour storage compared with 1-year storage

The comparison between the 24-hour storage and the 1-year storage can be made on different basis. In this chapter the saving of energy over the year is discussed as the difference of maximum power. The time of the period when the two types of storages can be used is also compared. Finally, the results from the calculations of the response in the pipe and ground systems for the two systems are discussed.

When comparing the saving of energy for the 24-hour storage with the 1-year storage it can be seen that the long term storage can save more energy over the whole year than the short term storage. The short term storage can theoretically save

34 % of total heating demand for the whole year (includes energy for HP)
17 % of total cooling demand for the whole year

And the long term storage can save

97 % of total heating demand (includes energy for HP)
57 % of total cooling demand

That means that allot more energy can be saved for the seasonal basis system than the 24-hour basis system. It is important to see these, not as absolute values since it is probably more losses in a system used in practice compared to what is considered in this thesis. Thus the losses from for example a fan or another air handling unit are often losses giving heat. If the machines are placed indoors they affect the indoor climate.

When turning from cooling to heating mode the power of energy that can be taken out from the pipe increases, this is due to bigger temperature potentials. But this increase in power will not be beneficial for the 24-hour basis storage compared with the seasonal storage if the seasonal storage is allowed to also to change mode on a daily basis during spring and autumn, as in the calculations. If comparing Figure 7.24 and Figure 7.35 it can be seen that the seasonal storage will work in the same temperature rages during springtime and autumn as the 24-hour basis storage.

The time of the year that the 24-hour basis storage can be in use is Figure 7.25 is studied visually, about 50 percent of the year. This is compared with 100% for the seasonal basis storage. Since the 24-hour storage only can be in use 50% of the year it means that less energy can be saved but also that the highest peaks of power of heating powers will not be dampened at all, since they are in the middle of the summer. The peaks when using seasonal basis storage cannot be covered totally by the storage but the can be lowered a bit all over the year.

Due to the short period of time between heating mode and cooling mode the amount of energy that has to be stored at the same time is not as big for the 24-hour basis storage as for the seasonal basis storage. The advantage having less energy in the ground at the same time is that less volume of the ground around the pipes needs to be used. If comparing Figure 7.22 and Figure 7.33 it can be seen that the seasonal basis storage affects volume about 1.5 meter radius around the pipe and the seasonal basis storage affects about 4 meter radius around the pipe. This means that a bigger volume of the ground is needed to be able to store the energy over seasonal basis. The difference in use of volume in ground also means that the seasonal basis storage needs to be placed further down in the ground. If the storage is placed under a free surface and should not be affected by the outdoor temperature, it has to be placed further down in the ground than the intrusion depth of the outdoor temperature over the year. If it is placed under a building, it has to be investigated to what extent the building will affect the temperature beneath the building. It may also be more beneficial to use vertical pipe system than a horizontal one placed for the seasonal storage system; this is due to that the horizontal system has to be placed so deep for the seasonal basis storage.

The total length of the pipes does not differ much between the 24-hour basis storage than the total length for the seasonal basis storage. This is simplified because the length of the pipe is mostly due to the power that needs to be entered or released from the ground. The need of cooling power during summer is greater than the need of heating or cooling power during the rest of the year. But since the highest peaks of the cooling power during summer are neglected for the seasonal storage, the length of the pipes does not have to be much longer for the seasonal storage than for the 24-hour basis storage, 8 pipes compared with 6 pipes of 400 meters.

8.3 Influence of temperature at surface

The temperature at surface, in this case the basement, will affect the function of the system. This is due to the heat exchanger in the cooling system. If the heat exchanger should work the fluid needs to be cold enough when leaving the ground to be able to take enough energy from the fluid in the cooling system in the building. Placing the pipe system too close under a building with high temperature may therefore not be suitable. How far below the building the temperature of the surface temperature is influenced is not investigated. This is also due to the size of the building, i.e. how far down under the building the ground is heated. If placing the pipes under this region the temperature of the ground around the pipes is the annual mean temperature of 8 degrees. Thus for a bigger house the heated region increases in depth. So for this 70 times 70 meters house, the unaffected ground may be further down than reasonable for horizontal placed underground thermal energy storage.

A way to get around the surface temperature problem could be to increase the outtake of energy a bit to compensate for the entering of energy from the boundary temperature at the surface. But for the object in the calculations the outtake of heat energy from the ground is the limitation for the storage, because the energy demand for heating of the building is smaller than the cooling demand. Therefore a system that takes out more energy, just to compensate for influence of high surface temperature, decreases its possibility to take care of the cooling demand of the building. If anyway using this possibility, the insulation on the ground surface can be increased to lower the need for heat outtake to compensate for high temperature at surface.

A reasonable maximum temperature in the basement for 24-hour storage is 12 degrees since the outside mean temperature during the month when the 24-hour storage can be used is about 10 degrees. If the basement is well ventilated it should be possible to keep the temperature down under 12 degrees. For this situation it is possible to design functioning heat and cold storage.

9 Conclusion

The result of the thesis shows that the building has a change of heating and cooling demand from night to day both during spring and autumn. The period when the 24-basis storage can be used is therefore limited. The time of this period depends on the type of building and on the surrounding climate. The time of the period is also sensitive to changes of requirements of indoor climate and variables in the building, as change of heat capacity and variation of size and duration of internal loads. If a building has internal loads that are extra high, it may be of greater interest to use the storage with a 24-hour basis. Also if the building has low heat capacity, it could be more beneficial to save the energy for heating and cooling in storage.

The heat and cold storage in the ground uses less space for the 24-hour basis storage than for the seasonal basis storage. That means that the pipes can be placed less deep and more close to each other. The functionality of the storage can also depend on the temperature on the ground surface.

The savings with using heat storage on a 24-hour basis is much due to the behaviour of the demand from the building. For the object in the calculation the savings are small but if the goal with the technical system is to reach a requirement for energy performance the solution could be enough. Thus if the point is to save energy, the storage on a seasonal basis is more favourable, since this also can work on a daily basis under the periods when the cooling and heating demand is shifting from day to night. The conclusion for the object in the calculations is that the storage on a 24-hour basis cannot save as much energy as storage on seasonal basis. But the 24-hour storage can help to lower the energy demand of energy from outside for heating and cooling during spring and autumn.

10 References

Boverket (2009): *Regesamling för byggande, BBR, Supplement februari 2009, 9 Energihushålling (Building* Regulations, BBR, Supplement February 2009, 9 Energy management). Boverket, Karlskrona, Sweden. Accessible at: www.boverket.se

Boverket (2010): *Konsekvensutredning- Revidering av avsnitt 9 (remissutskick)(Investigations of consequencies- Revision of part 9 (submission for comments).* Boverket, Karlskrona, Sweden. Accessible at: www.boverket.se

Claesson, Johan., Dunand, Alain (1983). *Heat extraction from the ground by horizontal pipes*. D1:1983 Swedish Council for Building Research.

Energimyndigheten (2010) : *Uppdrag 13: Nationell strategi för lågenergibyggnader (National strategy for low energy buildings).* Statens energimyndighet, Sweden. Accessible at: www.energimyndigheten.se

Forum för Energieffektiva byggnader (2009), *Kravspecification för passivhus (Requierment specification for Passive houses).* Forum för energieffektiva byggnader, Sweden. Accessible at: www.passivhuscentrum.se

Hagentoft, Carl.-Eric (2001). Introduction to building physics. Studentlitteratur. Lund, Sweden

Heat Pump Centre: *Heat Sources*. IEA Heat Pump Centre. Accessible at: http://heatpumpcentre.org

Installationsteknik (2003). *Värmeöverföring, strömningssystem och fuktig luft (Heattransfer, flow systems and humid air).* VIN086:2 2000. Gothenburg

Karlsson, Henrik. (2010). *Thermal Modelling of Water-Based Floor Heating Systems*. Department of Civil and Environmental Engineering. Gothenburg: Chalmers University of Technology.

Lindholm, Torbjörn (2009): *Air-conditionind, refrigeration and heat pump technology.* Compendium K2009:01. Chalmers University of Technology, Gothenburg.

Lund, J., Sanner, B., Rybach L., Curtis, R., Hellström, G. (2004) *Geothermal (Ground-Source) heat pumps - A world overview.* Vol 25, No. 3. Geo Heat Center. Accessible at: http://geoheat.oit.edu,

Lundström, Henrik (2009*): Välj rätt marklager (Choose the right Ground Storage System).* Energi och miljö No. 8, 2009, Energi och miljötekniska föreningen

MathWorks (2010), *MATLAB The language of technical computing,* R2010A

SGU, *Förnybara energikällor i sverige (Renewable energy sources in Sweden).* Sveriges Geologiska undersökning. Accessible at: www.sgu.se

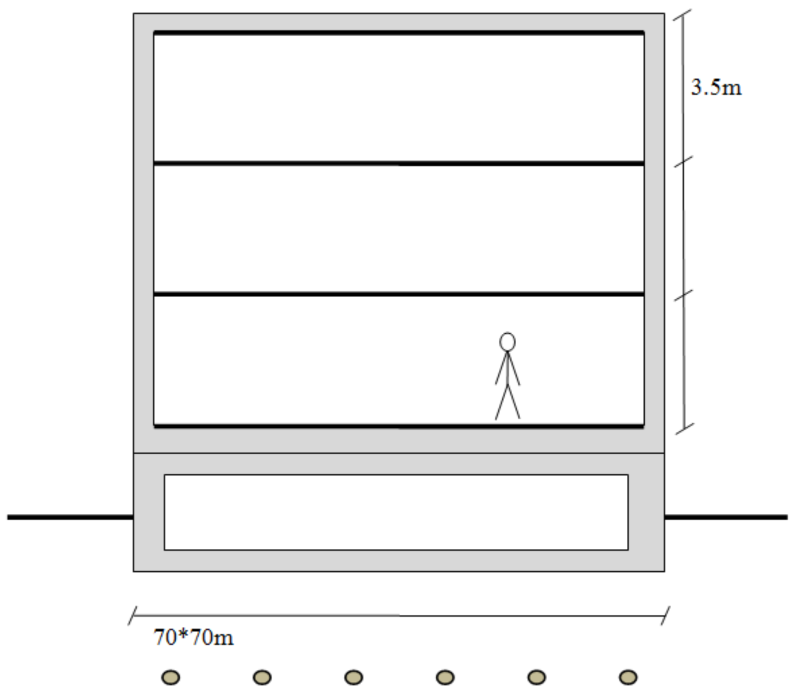
Wang, Jinkai (1998). *Heat and gas transfer in gas-filled insulation foams.* Department of Building Physics. Gothenburg: Chalmers University of Technology. Gothenburg

Appendix I

Description of the building used in the calculations

Geometry

Geometry of building
Length building: 70m
Width: Building: 70m
Height floors: 3.5m
Number of floors 3



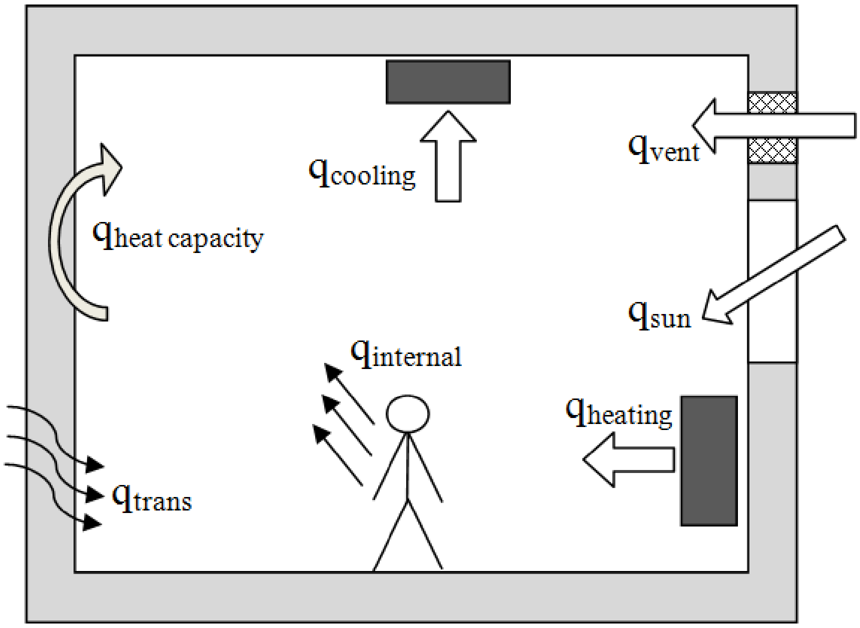
Geometry of pipe system
Length pipe: 400 m
Number of pipes: To be decided
Thickness pipe: 2.5 mm
Outer diameter pipe: 40 mm

Material data

In the table below the data for the material used in the calculation can be seen. The values for the boxes with "-" in the table are not used in the calculations and therefore not given.

Material	Density, ρ [kg/m3]	Heat capacity, c [Ws/(kg,K)]	Thermal Conductivity, λ [W/(mK)]	Volumetric heat capacity, ρ* c [J/(m^{3}K)]	Dynamic viscosity [kg/(ms)]
Air	1.2	1000	-	-	-
Concrete	2300	900	-	-	-
Water	1000	4200	0.6	-	0.001308
Clay	-	-	1.5	$3.0*10^6$	-
Insulation	-	-	0.038	-	-
Plastic	-	Neglected	0.2	-	-

Heat loads and heat gains



Internal heat production

Daytime is between 6 in the morning to 6 in the evening.

$q_{internal\ day}$=(5+1.5+3)=9.5 [W/m2] Lights, persons , machines

$q_{internal\ night}$ =0.2 [W/m2] Lights

Heat gains due to sun

The heat gain due to sun is taken from a data file calculated in the energy calculation program VIP energy. The building used in this thesis has been is modeled in the program and the heat gains due to sun has been exported for each hour of the year. The program is taking care of the geometry of the building and the square meter window. The area window is 40 % the façade area. The used data for sunshine is characteristic for Gothenburg.

Transmission
The U value used in the calculations is a mean value, and used for the whole building envelope. The Um value used is

U_m= 0.256 [W/m2K]

The outside temperature is taken from a data file with temperatures each hour during a yer in Copenhagen.

Ventilation
v_{day}=1.5 [l/s,m2]
v_{night}=0.25 [l/s,m2]

The outside temperature is taken from a data file with temperatures each hour during a yer in Copenhagen.

Heat capacity
The heat capacity in the building is the volume of 10 cm concrete over the building envelope area.

Technical data and temperature limitations

Indoor temperatures
The indoor temperature demands are:

$T_{indoor\ min}$=21°C
$T_{indoor\ max}$=23°C

Heating system
The coefficient of performance used is

COP=3

The heating system are not allowed to return a lower temperature than 0 degrees to the pipe system in the ground

Cooling system
The cooling system is working between the temperatures 14/17 °C. It is the fluid rate in the system that varies due to the cooling demand. The heat exchanger between the fluid in the cooling system and fluid in the pipe system is seen to be ideal but with a temperature drop of 1 degrees, i.e., the fluid in the pipe system can with the return temperature of 17 °C from the cooling system at max be heated to 16°C.

Flow in each pipe
v_{fluid}=0.45 [l/s]

Appendix II
MATLAB Code

```
%-------------------------------------------------------------------
------
%Lisa Olausson
%2011-05-26
%-------------------------------------------------------------------
------
clear all
close all
clc
%-------------------------------------------------------------------
%         ---------------INPUT FROM USER--------------
%-------------------------------------------------------------------
%Pipe
num_segments=10;            %[-]
plot_segment=5;
%Radius
num_elements=9;             %[-] Number of anumlus to split the
ground into
r_outer=4;                  %[m] Outer boundary of the ground

%-----MATERIAL DATA
%GROUND
%Clay
lambda_ground=1.5;          %[W/(mK)] Thermal conductivity
roc_ground=3.0e6;           %[J/(m^3K)] Volumetric heat capacity
%Pipe
lambda_pipe=0.2;
%Insultaion
d_ins=0.20
lambda_ins=0.038;
%Fluid=WATER
lambda_fluid=0.6;           %[W/(mK)] Thermal conductivity
ro_fluid=1000;              %[kg/m3] Density
c_fluid=4200;               %[Ws/(kgK)] Specific heat capacidy
dyn_visk_fluid=0.001308;    %[kg/(m·s)] or [N·s/m2] Dynamic viscosity
%ny*ro %IV-8 i Embedded water-based surface heating- Henrik Karlsson.
                            %vid 10C från boken
                            %värmeöverföring,strömninssystem fuktig
luft
%Air
ro_air=1.2; %[kg/m3]
c_air=1000; %[Ws/kgK]
%Concrete
ro_concrete=2300;    %[kg/m3]
c_concrete=900;      %[Ws/kgK]

%-----INTERNAL LOADS AND VENTILATION
Q_day=(5+1.5+3); %[W/m2]
Q_night=0.2;%[W/m2]
v_day=1.5/1000; %[m3/s,m2]
v_night=0.25/1000;%[m3/s,m2]

%-----GEOMETRY
%Building
d_longside=70;
```

```
d_shortside=70;
number_floor=3;
height_floor=3.5;
thickness_wall=0.10;%[m]
%Pipe
t_pipe=0.0025;
d_pipe=0.040-t_pipe*2;%0.035;         %[m] Inner diameter of pipe
0.035
length_pipe=400; %[m] Length of pipe

%-----INITIAL TEMPERATURES
%BUILDING
Tindoor_start=21;%[C]
T_initial_ground=8;
TF_start=8;

%-----TECHNICAL DATA FOR SYSTEM
%Temperatures over the cooling unit
TFbaff=14;  %Entering
TRbaff=18;  %Return
%Coeffictient of performance
COP=3;
Um=0.256; %[W/m2K] With cold bridges

Tindoor_min=21;
Tindoor_max=23;

T_basement=12;
d_to_surf=5; %[m] distace from center of pipe to surface
Vfluid=0.45/1000; %Volume flow in the pipe [m3/s]

%--------------------------------------------------------------------
------
%WHEN IS THE CALCULATION PERIOD AN WHAT SHOULD BE CALCULATED?
start_month=4;
start_days=1;
how_many_month=1;
how_many_days=30; %Should be 30 if more than a month
calculateground=1;
fixalast=1;
fler=0;
repetitions=0;
Toutletdemands=0;
    Toutlet_demand_min=4;
    Toutlet_demand_max=12;
T_basement=8;
r_outer=8;
d_to_surf=9;
n_pipes=8;

%För 10 dagar
% T_initial_ground=8;
% n_pipes=6;
% start_month=4;
% start_days=10;
% how_many_month=12;
% how_many_days=30; %Should be 30 if more than a month
% calculateground=1;
% fixalast=0;
% fler=0;
```

```
% repetitions=0;
% Toutletdemands=1;
%       Toutlet_demand_min=4;
%       Toutlet_demand_max=12;
% r_outer=5%1.5;
% d_to_surf=2;
% T_basement=8;
%-----------------------------------------------------------------------
------

load TemperaturKopenhamnOchSol.txt
climatedata=TemperaturKopenhamnOchSol;

calculationtime=3600*24*how_many_days*how_many_month;
starthour=30*(start_month-1)*24+(start_days-1)*24;%

%---------GEOMETRY ground and pipe-----------------------------------
------
r_inner=d_pipe/2;
explr=exp(log(r_outer/(r_inner+t_pipe))/(num_elements));

radius=zeros(num_elements+1,1);
for r=1:num_elements+1
    radius(r,1)=(r_inner+t_pipe)*exp((r-1)*log(explr));
end

%radius=[r_inner:(r_outer-r_inner)/num_elements:r_outer]';
element_nodes_R=[radius(1:end-1),radius(2:end)];
midpoint_element=(element_nodes_R(:,2)+element_nodes_R(:,1))/2;

%pipe
length_segments=length_pipe/num_segments;
start_segments=[0:length_segments:length_pipe];

%---------GEOMETRY climate in house----------------------------------
------
A_around=(d_longside+d_shortside)*2*number_floor*height_floor+(d_long
side*d_shortside)*2;
V_house=d_longside*d_shortside*(number_floor*height_floor);
A_floors=d_longside*d_shortside*number_floor;
V_concrete=(d_longside*2+d_shortside*2)*(number_floor*height_floor)*t
hickness_wall;

C_concrete=ro_concrete*c_concrete*V_concrete;
C_air=ro_air*c_air*V_house; %kg/m3*Ws/kgK*m3=Ws/K

mflow_tot=Vfluid*ro_fluid;
%-----------------------------------------------------------------------
-----
%SURFACE RESISTANCE ON THE INSIDE OF THE PIPE
reynold=4*ro_fluid*Vfluid/(pi*dyn_visk_fluid*2*r_inner);
if reynold < 2300
    nusselt=4;
else %För medier med måtlig densitet kan detta användas från 2300
TURBULENT
    prandlt=dyn_visk_fluid*c_fluid/(lambda_fluid); %eq.3.34
    nusselt=0.023*reynold^(0.8)*prandlt^(0.35); %Eq3.41 Tar mitt
emelan kyler och värmer
end
R_surface=1/(pi*lambda_fluid*nusselt); %Ok eq 3.38
```

```
%-----------------------------------------------------------------------
%CONDUCTIVITY IN GROUND - CONSTANT OVER WHOLE CALCULATION
Kr=zeros(1,num_elements+1);
for i=1:num_elements+1
    if i==1
        R_right(i)=(log(midpoint_element(i))-
log(element_nodes_R(i,1)))/(2*pi*lambda_ground);

        R_pipe=log((r_inner)/(r_inner+t_pipe))/(2*pi*lambda_pipe);

        Kr(i)=1/(R_right(i)+R_surface);
    elseif i==num_elements+1
        R_left(i)=(log(element_nodes_R(i-1,2))-
log(midpoint_element(i-1)))/(2*pi*lambda_ground);

R_right_ins=log((d_to_surf+d_ins)/d_to_surf)/(2*pi*lambda_ins);

R_right_ground=log((2*d_to_surf)/r_inner)/(2*pi*lambda_ground)+R_righ
t_ins-(sum(R_right)+sum(R_left));
        Kr(i)=1/(R_left(i)+R_right_ground);
    else
        R_right(i)=(log(midpoint_element(i))-
log(element_nodes_R(i,1)))/(2*pi*lambda_ground);
        R_left(i)=(log(element_nodes_R(i-1,2))-
log(midpoint_element(i-1)))/(2*pi*lambda_ground);
        Kr(i)=1/(R_right(i)+R_left(i));               %page 35 Jinkai
Wang
    end
end

%In matrix
place=2;
K=zeros(length(Kr)-1,length(Kr)-1);
for N=1:length(Kr)-2
into=[-1 1;1 -1]*Kr(place);
K(N:N+1,N:N+1)=K(N:N+1,N:N+1)+into;
place=place+1;
end

%-----------------------------------------------------------------------
%-----------------------------------------------------------------------
%STABLE TIME STEP
time_stable_element=zeros(1,num_elements);
for i=1:num_elements
time_stable_element(i)=(element_nodes_R(i,2)^2*pi-
element_nodes_R(i,1)^2*pi)*roc_ground./(Kr(i)+Kr(i+1));%element_delta
_R(i)*roc_ground./(Kr(i)+Kr(i+1));%-R_surface); %obs surface
resistancen är INTE med....ska den va de
end
time_stable=0.95*min(time_stable_element);
%-----------------------------------------------------------------------
------
%Initial values
t=0.001:time_stable:calculationtime;
%-----------------------------------------------------------------------
%för denna loop
Tindoor2=zeros(1,length(t));
Tindoor2(1)=Tindoor_start;
```

```
Tout=zeros(1,length(t)-1);

Tindoor=zeros(1,length(t));
Tindoor(1)=Tindoor_start;
deltaTindoorcheck2=zeros(1,length(t)-1);
Tindoorcheck2=zeros(1,length(t)-1);

deltaTindoor_demand2=zeros(1,length(t)-1);
deltaTindoor2=zeros(1,length(t)-1);

Qheater2=zeros(1,length(t)-1);

system2=zeros(1,length(t)-1);
Qcooler2=zeros(1,length(t)-1);
Qtrans=zeros(1,length(t)-1);

Qvent=zeros(1,length(t)-1);
Qint=zeros(1,length(t)-1);
qsol=zeros(1,length(t)-1);
Qtot=zeros(1,length(t)-1);
        Qtot2=zeros(1,length(t)-1);

Qinstallation=zeros(1,length(t)-1);

integrerad=zeros(1,length(t)-1);

%---------------------------------------------------------------------
%CALCULATES COOLING AND HEATING DEMAND
%---------------------------------------------------------------------
for num=[1:length(t)-1]

    %-----------------------------------------------------------------
    %CALCULATES HEAT LOSS AND HEAT GAIN
    %-----------------------------------------------------------------
    %Time of the year
    year_hours=8760*floor((starthour+floor(t(num)/3600))/8760);
    hour=starthour+ceil(t(num)/3600)-year_hours;
    if hour-1==0
    x=8760;
    else x=0;
    end
    %Get outside temperature
    ToutA=climatedata(x+hour-1,2);
    ToutB=climatedata(hour,2);
    %Hour of the day
    inhour=t(num)/3600-floor(t(num)/3600);
    Tout(num)=inhour*(ToutB-ToutA)+ToutA;
    qsol(num)=climatedata(hour,3)*1000;%kW*k=W
    %Tout(num)=-10;

    %INTERNAL LOADS
    whenonday=hour-floor(hour/24)*24;
    if whenonday<=6 ||  whenonday>=18
            vent=v_night;
            Qintern=Q_night*A_floors;
    else
            vent=v_day;
            Qintern=Q_day*A_floors;
    end
```

```
        Qint(num)=Qintern;


    %TRANSMISSION
    Qtrans(num)=Um*A_around*(Tout(num)-Tindoor(num)); %W/m2K*m2*K=W

    %VENTILATION
    %Heat exchanger
    nt=0.8;
    nV=vent*A_floors;%[m3/sm2*m2]=m3/s;
    if Tout(num)<18 % Lower demand of inlet temperature for comfort
        Ttill=Tindoor(num)+(1-nt)*(Tout(num)-Tindoor(num));
        Qvent(num)=(Ttill-Tindoor(num))*nV*ro_air*c_air;
    else
        Qvent(num)=nV*ro_air*c_air*(Tout(num)-Tindoor(num));
    end

    %TOTAL HEAT LOSS OR HEAT GAIN
    Qtot(num)=(Qtrans(num)+Qint(num)+Qvent(num)+qsol(num)); %W
    Qtot2(num)=Qtot(num);


deltaTindoorcheck2(num)=(Qtot2(num))./(C_air+C_concrete)*(t(num+1)-
t(num));
    Tindoorcheck2(num)=Tindoor2(num)+deltaTindoorcheck2(num);

        if Tindoorcheck2(num)<=Tindoor_min;
        deltaTindoor_demand2(num)=Tindoor_min-Tindoor2(num);

Qheater2(num)=(deltaTindoor_demand2(num)*(C_air+C_concrete)/(t(num+1)
-t(num)))-(Qtot2(num));
            Qinstallation(num)=Qheater2(num);
            system2(num)=3;
        elseif Tindoorcheck2(num)>=Tindoor_max;
        deltaTindoor_demand2(num)=Tindoor_max-Tindoor2(num);

Qcooler2(num)=(deltaTindoor_demand2(num)*(C_air+C_concrete)/(t(num+1)
-t(num)))-(Qtot2(num));
            Qinstallation(num)=Qcooler2(num);
            system2(num)=1;
        else
        Qheater2(num)=0;
        Qcooler2(num)=0;
        Qinstallation(num)=0;
        system2(num)=2;
        end

    %-----------------------------------------------------------------
    %INDOOR TEMPERATURE
    %-----------------------------------------------------------------

    integrerad(num)=sum(Qinstallation)*time_stable;

deltaTindoor2(num)=(Qtot2(num)+Qinstallation(num))/(C_air+C_concrete)
*(t(num+1)-t(num));
    Tindoor2(num+1)=Tindoor2(num)+deltaTindoor2(num);

    Tindoor(num+1)=Tindoor2(num+1);
```

```
end
%----------------------------------------------------------------------
%Plotta
%----------------------------------------------------------------------
 %---'Cooling and heating demand'
tplot=t;
tplot(length(tplot))=[];
figure('name','Cooling and heating demand','NumberTitle','off')
plot(tplot/(3600*24),Qheater2/1000,'r','LineWidth',1)
hold on
plot(tplot/(3600*24),Qcooler2/1000,'b','LineWidth',1)
title('\fontsize{16} Cooling and heating demand')
xlabel('\fontsize{12}Time [Days]')%
ylabel('\fontsize{12}Power [kW]')
axis([ 0,max(tplot)/(3600*24) , floor(min(Qcooler2/1000)),
ceil(max(Qheater2/1000))])

%---'integrerad'
figure('name','integrerad','NumberTitle','off')
plot(tplot/(3600*24),integrerad/10^9,'b','LineWidth',1)
title('\fontsize{16}Sum of cooling and heating demand over time')
xlabel('\fontsize{12}Time [Days]')%
ylabel('\fontsize{12}Energy  [10^9 J]')
axis([ 0,max(tplot)/(3600*24) , floor(min(integrerad/10^9)),
ceil(max(integrerad/10^9))])

%---'Tute och för krav'
figure('name','Tute och för krav','NumberTitle','off')
    subplot('position',[0.1 0.4 1-(0.2)
0.5]),plot(tplot/(3600*24),Tout,'k','LineWidth',1)
    axis([ 0, max(tplot)/(3600*24)  , -10, 30])
    hold on
    Tindoorplot2=Tindoor2;
    Tindoorplot2(length(Tindoorplot2))=[];
    subplot('position',[0.1 0.4 1-(0.2)
0.5]),plot(tplot./(3600*24),Tindoorplot2,'r','LineWidth',1)
    title('\fontsize{16}Temperature outside and in building')
    legend('Outdoor temperature','Indoor
temperature','location','SouthOutside')%,'location','SouthOutside
    ylabel('\fontsize{12}Temperature [\circC]')
    xlabel('\fontsize{12}Days')

    subplot('position',[0.1 0.1 1-(0.2)
0.2]),plot(tplot./(3600*24),system2-1,'b','LineWidth',1)

    axis([ 0, max(tplot)/(3600*24) , -0.5, 2.5])
    legend('0=cooling, 1=off, 2=heating','location','SouthOutside')
    ylabel('\fontsize{12}Mode on climate unit')
    xlabel('\fontsize{12}Days')

%---------------------------
figure('name','Transport and production of power over
time','NumberTitle','off')
    plot(tplot./(3600*24),Qtrans/1000,'r')
    hold on
    plot(tplot./(3600*24),Qvent/1000,'b')
    plot(tplot./(3600*24),Qint/1000,'c')
    plot(tplot./(3600*24),Qinstallation/1000,'k')
    plot(tplot./(3600*24),qsol/1000,'y')
```

```
legend('Qtrans','Qvent','Qint','Qinstallation','qsol')
title('\fontsize{16}Transport and production of effect over time')
xlabel('\fontsize{12}Time for calculation [Days]')
ylabel('\fontsize{12}Power [kW]')


Xar=(calculationtime/(8760*3600));
delar=1/(Xar);
energiheater2=sum(Qheater2)*time_stable;
energicooler2=sum(Qcooler2)*time_stable;

energivarme2KWH=energiheater2/3600000;
energikyla2KWH=energicooler2/3600000;

energivarmeKWHyearochm2=energivarme2KWH/A_floors*delar;
energikylaKWHyearochm2=energikyla2KWH/A_floors*delar;

disp([num2str(energivarme2KWH) ' kWh totalt under beräkningstiden'])
disp([num2str(energikyla2KWH) ' kWh totalt under beräkningstiden'])

disp([num2str(energivarmeKWHyearochm2) ' kWh/m2ochår till värme
ofixad'])
disp([num2str(energikylaKWHyearochm2) ' kWh/m2ochår till kyla
ofixad'])

%---------------------------------------------------------------------
%CALCULATES MODIFIED DEMANDS
%---------------------------------------------------------------------

if fixalast==1
        figure('name','qfixad','NumberTitle','off')

%plot(tplot/(3600*24),Qinstallationfixad/1000,'g','LineWidth',2)
        plot(tplot/(3600*24),Qheater2/1000,'r','LineWidth',1)
        hold on
        plot(tplot/(3600*24),Qheater2/1000*(1-
1/COP),'k','LineWidth',1)
        plot(tplot/(3600*24),Qcooler2/1000,'b','LineWidth',1)
        axis([ 0,max(tplot)/(3600*24) , floor(min(Qcooler2)/1000),
ceil(max(Qheater2)/1000)])
    integreradQheater2=sum(Qheater2)*time_stable;
    integreradQheater2_COP=integreradQheater2-integreradQheater2/COP;
    integreradQcooler2=sum(Qcooler2)*time_stable;
    partoff=integreradQheater2_COP/-integreradQcooler2;
    if partoff<1 %Greated heating than cooling demand=> Modify
cooling
    Qcooler2fixad=Qcooler2.*partoff;
    Qinstallationfixad=Qcooler2fixad+Qheater2;
    koll=integreradQheater2_COP/(-sum(Qcooler2fixad)*time_stable)%Ska
va =1


plot(tplot/(3600*24),Qcooler2fixad/1000,'g','LineWidth',1)
            legend('Heating demand','Heat from storage','Cooling
demand','Cooling required from storage','location','SouthEast')

Xar=(calculationtime/(8760*3600));
delar=1/(Xar);
energivarmefixad2KWH=sum(Qheater2)*time_stable/3600000;
```

```
energikyla2KWHfixad=sum(Qcooler2fixad)*time_stable/3600000;
energivarmeKWHyearochm2=energivarme2KWH/A_floors*delar;
energikylaKWHyearochm2fixad=energikyla2KWHfixad/A_floors*delar;

muchHEATtostorage=energivarmefixad2KWH/energivarme2KWH;
disp([num2str(energivarmefixad2KWH) ' kWh totalt under
beräkningstiden fixad(ej)=' num2str(muchHEATtostorage*100)])
muchCOOLtostorage=energikyla2KWHfixad/energikyla2KWH;
disp([num2str(energikyla2KWHfixad) ' kWh totalt under beräkningstiden
fixad=' num2str(muchCOOLtostorage*100)])
disp([num2str(energivarmeKWHyearochm2) ' kWh/m2ochår till värme
fixad(ej)'])
disp([num2str(energikylaKWHyearochm2fixad) ' kWh/m2ochår till kyla
fixad'])



    elseif partoff>1 %fixa heater
        partoffheat=-integreradQcooler2/integreradQheater2_COP;

    Qheater2_ground_fixad=(Qheater2-Qheater2/COP).*(partoffheat);

    Qheater2fixad=Qheater2_ground_fixad+Qheater2_ground_fixad/COP;

    Qinstallationfixad=Qheater2fixad+Qcooler2;
    koll2=-integreradQcooler2/(-
sum(Qheater2_ground_fixad)*time_stable)%Ska va =1

plot(tplot/(3600*24),Qheater2fixad/1000,'g','LineWidth',1)

                legend('Heating demand','Heat from storage','Cooling
demand','Heat required from storage','location','SouthEast')

    end
    Qinstallationdemand=Qinstallationfixad;

else
    Qinstallationdemand=Qinstallation;
end

title({'\fontsize{16}Cooling-, heating-, and part of  ' 'cooling
demand required from storage'})
xlabel('\fontsize{12}Time [Days]')
ylabel('\fontsize{12}Power [kW]')



if fixalast==1
Qinstallationfixad_integrerad=zeros(1,length(t)-1);
for i=[1:length(t)-1]
    if partoff<1
    Qinstallationfixad_integrerad(i)=sum(Qheater2(1:i)*(1-
1/COP)+Qcooler2fixad(1:i))*time_stable;
    elseif partoff>1

Qinstallationfixad_integrerad(i)=sum(Qheater2_ground_fixad(1:i)+Qcool
er2(1:i))*time_stable;
    end
end
```

```
figure('name','integrerad2','NumberTitle','off')
plot(tplot/(3600*24),Qinstallationfixad_integrerad/10^9,'b','LineWidt
h',1)
hold on
title({'\fontsize{16}Sum of fixed cooling and heating energy '
'required from storage over time'})
xlabel('\fontsize{12}Time [Days]')%
ylabel('\fontsize{12}Energy  [10^9 J]')
axis([ 0,max(tplot)/(3600*24) ,
floor(min(Qinstallationfixad_integrerad/10^9)),
ceil(max(Qinstallationfixad_integrerad/10^9))])
end

% Repeat the period of modified demands.
if fler==1
Qinstallationdemand_fler=Qinstallationfixad;
Qheater2_fler=Qheater2;
Qcooler2_fler=Qcooler2;
system2_fler=system2;
for s=1:repetitions
Qinstallationdemand_fler=[Qinstallationdemand_fler
Qinstallationdemand];
Qheater2_fler=[Qheater2_fler Qheater2];%Tot demand
Qcooler2_fler=[Qcooler2_fler Qcooler2];%Tot demand
system2_fler=[system2_fler system2];
end
t=0.001:time_stable:length(Qinstallationdemand_fler)*time_stable;
Qinstallationdemand=Qinstallationdemand_fler;
system2=system2_fler;
Qheater2=Qheater2_fler;
Qcooler2=Qcooler2_fler;
Qcooler2(end)=[];
Qheater2(end)=[];

end

%-----------------------------------------
%SET SIZE OF VECTORS FOR FASTER LOOP

system=zeros(1,length(t)-1);
TR=zeros(1,length(t)-1);
TF=zeros(1,length(t)-1);
TF(1)=TF_start;
v_baff=zeros(1,length(t)-1);
Qcooling=zeros(1,length(t)-1);
Qcooling_exchange=zeros(1,length(t)-1);
Qcooling_additional=zeros(1,length(t)-1);
Qheater=zeros(1,length(t)-1);
Qheater_tot_VP=zeros(1,length(t)-1);
Qheater_electric_VP=zeros(1,length(t)-1);
Qheater_additional=zeros(1,length(t)-1);

Qdemand=zeros(1,length(t)-1);

T_fluid_inlet=zeros(1,length(t)-1);
T_fluid_outlet=zeros(1,length(t)-1);
T_pipe_save=zeros(num_segments+1,length(t)-1);
T_ground=ones(num_elements,num_segments)*T_initial_ground;
save_T_ground=zeros(num_elements,length(t)-1);
Watt_spara_hela_roret=zeros(1,length(t)-1);
```

```
Energy_tot_segments=zeros(1,length(t)-1);
Energy_tot=zeros(1,length(t)-1);
Q_relased_fluid=zeros(1,length(t)-1);
Q_relased_fluid_tot=zeros(1,length(t)-1);
nextsystemtemp=zeros(1,length(t)-1);

%---------------------------------------------------------------------
------
%NOTE: From now on, calculates for n_pipes
if calculateground==1
    percentage=0;
    w=waitbar(0,'Please wait...');
    nextsystem=0 ;
    lastsystem=4;
    Qinstallationdemand=Qinstallationdemand/n_pipes;
for num=[1:length(t)-1]
    if num/(length(t)-1)>percentage
    w=waitbar(num/(length(t)-1));
    percentage=percentage+0.05;
    end

    %-----------------------------------------------------------------
    %SYSTEM FOR TAKING CARE OF HEAT LOSS AND HEAT GAINS
    %-----------------------------------------------------------------
    %--------COOLING--------
    %There is a limit of 1 degree difference between the water in...
    %baffelsystem and the water in pipe system.
    lost=1;
    if nextsystem==0
    if Qinstallationdemand(num)<0
        system(num)=1;

Qdemand(num)=Qinstallationdemand(num);%((deltaTindoorXkyl(num)*(C_air
+C_concrete)/(t(num+1)-t(num)))-(Qtot(num)))/n_pipes; %K WS/K 1/s= W

            v_baff(num)=-Qdemand(num)/(ro_fluid*c_fluid*(TRbaff-
TFbaff));
            %Check pipe inlet temperature.
            TR(num)=TF(num)+v_baff(num)*(TRbaff-TFbaff)/Vfluid;
%x+pos(17-14)/pos= bigger than TF
            if TR(num)<=TRbaff-lost
            %The heatexchanger can manage the temperature demands
            Qcooling_exchange(num)=Qdemand(num);
            %No electrical part needed.
            Qcooling_additional(num)=0;
            elseif TR(num)>TRbaff-lost
            %The heatexchanger can't manage the temperature
demands...
            %without extra cooling of the fluid in the baffel system.
            %The temperature after heatexchanger before VCM.
            TR(num)=TRbaff-lost;
            TF_VCM=TRbaff-Vfluid/v_baff(num)*(TR(num)-TF(num)) ; %12-
16
            %The electrical part of the cooling effect.
            Qcooling_additional(num)=-
ro_fluid*c_fluid*v_baff(num)*(TF_VCM-TFbaff);
            %The cooling effect
            %Qinstallation(num)=Qdemand(num);
            Qcooling_exchange(num)=Qdemand(num)-
Qcooling_additional(num);
            end
```

```
Qcooling(num)=Qcooling_additional(num)+Qcooling_exchange(num);

    %---------HEATING-----------
            elseif Qinstallationdemand(num)>0
            system(num)=3;
            Qheater_electric_VP(num)=Qinstallationdemand(num)/COP;
            TR(num)=TF(num)-(Qinstallationdemand(num)-
Qheater_electric_VP(num))/(mflow_tot*c_fluid); %K-W/(Ws/kgK*kg/s)=T-
w/(WK)=K%ändrat till electric VP utan att tänkt typ
            %Not allowed with temp in pipe under zero degrees
            if TR(num)<0

                %What can the heat pump take, down to zero degrees
                heatground=(TF(num)-0)*(mflow_tot*c_fluid);%from
ground
                Qheater_tot_VP(num)=heatground*COP/(COP-1);%Total
heat pump

                %Electricity for heatpump

                Qheater_electric_VP(num)=Qheater_tot_VP(num)/COP;
%Electric part

                %Extra electricity to manage heating demand.
                Qheater_additional(num)=Qinstallationdemand(num)-
Qheater_tot_VP(num);

Qheater(num)=Qheater_additional(num)+Qheater_tot_VP(num);
                TR(num)=0;

            else
                Qheater(num)=Qinstallationdemand(num);

                Qheater_tot_VP(num)=Qinstallationdemand(num);
            end

    %------NOTHING-------
    elseif Qinstallationdemand(num)==0

        TR(num)=TF(num);
        system(num)=2;
    end



    elseif nextsystem==1
        TR(num)=TF(num);
        system(num)=2;
    end

    %-----------------------------------------------------------------
    %CALCULATES TEMPERATURE DISTRIBUTION IN PIPE
    %-----------------------------------------------------------------

    T_fluid_inlet(num)=TR(num);

    Teq=T_ground(1,:);
    Req=1/Kr(1);
```

```
    lc=1/Kr(1)*Vfluid*c_fluid*ro_fluid; %(eq21) transvers/convective%
%lc=Req*Vfluid*c_fluid*ro_fluid;
    num_seg=1;
    T_pipe=zeros(1,num_segments+1);
        for kk=1:num_segments+1 %T0, L0 alfa 0 and Mprick constant in
each segment
            if kk==1
            T_pipe(kk)=T_fluid_inlet(num); %Teq(kk)+(Tfluid_in-
Teq(kk))*exp(-segment_delta_length(kk)/lc);
            else
            T_pipe(kk)=Teq(num_seg)+(T_pipe(kk-1)-Teq(num_seg))*exp(-
length_segments/lc);%(-segment_delta_length(num_seg)/lc);
            num_seg=num_seg+1;
            end
        end
    T_fluid_outlet(num)=T_pipe(num_segments+1);
    TF(num+1)=T_fluid_outlet(num); %T_pipe(num_segments+1);
    T_pipe_save(:,num)=T_pipe;

    %-----------------------------------------------------------------
    if Toutletdemands==1
    if nextsystem==0
        if TF(num+1)<=Toutlet_demand_min ||
TF(num+1)>=Toutlet_demand_max

            nextsystem=1;
            if system2(num)~=2
            lastsystem=system2(num);
            %Must be heat or coolled
            end
        end

    elseif nextsystem==1
        if num<length(t)-1
        if system2(num)~=system2(num+1) && lastsystem~=system2(num+1)
&& system2(num+1)~=2;  %Ändra tillbaka om byter till värme/kyla

        nextsystem=0;

        end
        end
    end
    nextsystemtemp(num)=nextsystem;
    end

    %-----------------------------------------------------------------
    %CALCULATES TEMPERATURE DISTRIBUTION IN GROUND
    %-----------------------------------------------------------------
    q_each_segment=zeros(1,num_segments);
    for i=1:num_segments
            q_delta=K*T_ground(:,i);
            Tpipe=T_pipe(i:i+1);
                f=zeros(length(K),1);
                f(1)=ro_fluid*c_fluid*Vfluid*(Tpipe(1)-
Tpipe(2))/length_segments;
                f(end)=-Kr(length(K)+1)*(T_ground(length(K),i)-
T_basement);

            deltaTjord2=(q_delta+f)./((element_nodes_R(:,2).^2-
element_nodes_R(:,1).^2).*roc_ground*pi).*time_stable;
```

```
            T_ground(:,i)=T_ground(:,i)+deltaTjord2;
            q_each_segment(i)=f(1);
        %------------------------------------------------------------
        %Collects data to plot
        if i==num_segments
            save_T_ground(:,num)=T_ground(:,plot_segment);

%save_T_ground_each_segment2(:,num)=T_ground_each_segment(:,20);
        end
    end

    %----------------------------------------------------------------
    %ENERGY GOING INTO THE GROUND
    q_flow_pipe=sum(q_each_segment*length_segments); %W
    Watt_spara_hela_roret(num)=q_flow_pipe;
    Energy_tot(num)=sum(Watt_spara_hela_roret)*time_stable;

    %----------------------------------------------------------------
    %ENERGRY RELEASED FROM FLUID
    Tin_Tout_delta=T_fluid_inlet(num)-T_fluid_outlet(num);

Q_relased_fluid(num)=ro_fluid*c_fluid*Vfluid*(time_stable)*Tin_Tout_d
elta;
    Q_relased_fluid_tot(num)=sum(Q_relased_fluid);

end
end
close(w)
%--------------------------------------------------------------------
%PLOT ALLOT
%--------------------------------------------------------------------
tplot=t;
tplot(length(tplot))=[];
%--------------------------------------------------------------------
figure('name','Temperature in climate unit over
time','NumberTitle','off')
    TF(length(TF))=[];
    plot(tplot/(3600*24),TF,'b','LineWidth',1.5)
    hold on
    plot(tplot/(3600*24),TR,'r--','LineWidth',1.5)
title('\fontsize{16}Temperature in climate unit over time')
xlabel('\fontsize{12}Time for calculation [Days]')
ylabel('\fontsize{12}Temperature [\circC]')
legend('TE-Entering temperature','TR-Return temperature','Tindoor
temperature', 'location','SouthOutside')
%--------------------------------------------------------------------
figure('name','Inlet and outlet of pipe','NumberTitle','off')
        plot(tplot./(3600*24),T_fluid_inlet,'b','LineWidth',1.5)
        hold on
        plot(tplot./(3600*24),T_fluid_outlet,'r--','LineWidth',1.5)
        axis([ 0,max(tplot)/(3600*24) , floor(min(T_fluid_inlet)),
ceil(max(T_fluid_inlet))+1])
title('\fontsize{16}Temperature at inlet and outlet of pipe over
time')
xlabel('\fontsize{12}Time for calculation [Days]')
ylabel('\fontsize{12}Temperature [\circC]')
legend('Inlet','Outlet','Location','SouthEast')
%--------------------------------------------------------------------
figure('name','Energy entering ground','NumberTitle','off')
    plot(tplot./(3600*24),Energy_tot/10^9*n_pipes,'b')
```

```
    axis([ 0,max(tplot)/(3600*24) ,
floor(min(Energy_tot/10^9*n_pipes)),
ceil(max(Energy_tot/10^9*n_pipes))])
    hold on
title('\fontsize{16}Energy entering ground over time')
xlabel('\fontsize{12}Time [Days]')%
ylabel('\fontsize{12}Energy  [10^9 J]')
%----------------------------------------------------------------------
figure('name','Power going into the ground','NumberTitle','off')
    plot(tplot./(3600*24),Watt_spara_hela_roret/1000*n_pipes,'b')
title('\fontsize{16}Power going into the ground')
%legend('EFFECT GOING INTO THE GROUND THROUGUOUT THE WHOLE
PIPE','Location','NorthEastOutside')
xlabel('\fontsize{12}Time [Days]')
ylabel('\fontsize{12}Power [kW]')
%----------------------------------------------------------------------
figure('name','Temperature distribution in pipe','NumberTitle','off')
for i=1:ceil(num/100):num
plot(start_segments,T_pipe_save(:,i))
hold on
end
title('\fontsize{16}Temperature distribution in pipe')
xlabel('\fontsize{12}Length [m]')
ylabel('\fontsize{12}Temperature [\circC]')
%----------------------------------------------------------------------
figure('name','Temperature distribution in
ground','NumberTitle','off')
for i=1:ceil(num/25):num
    plot(midpoint_element,save_T_ground(:,i));
    hold on
end
title('\fontsize{16}Temperature distribution in ground')
xlabel('\fontsize{12}Radius [m]')
ylabel('\fontsize{12}Temperature [\circC]')
%----------------------------------------------------------------------
figure('name','Power from storage and else per
pipe','NumberTitle','off')
hold on
    plot(tplot./(3600*24),Qcooling/1000*n_pipes,'b','LineWidth',2);
    hold on

plot(tplot./(3600*24),Qcooling_exchange/1000*n_pipes,'g','LineWidth',
1);
    plot(tplot./(3600*24),Qcooling_additional/1000*n_pipes,'k');
    plot(tplot./(3600*24),Qheater/1000*n_pipes,'r','LineWidth',2);

plot(tplot./(3600*24),Qheater_tot_VP/1000*n_pipes,'y','LineWidth',1);
    plot(tplot./(3600*24),Qheater_electric_VP/1000*n_pipes,'m');

plot(tplot./(3600*24),Qheater_additional/1000*n_pipes,'k','LineWidth'
,1);
title('\fontsize{16}How much from storage')
xlabel('\fontsize{12}Time for calculation [Days]')
ylabel('\fontsize{12}Power [kW]')
legend('Qcooling','Qcooling exchange','Qcooling
additional','Qheater','Qheater tot VP','Qheater electric VP','Qheater
additional')
%----------------------------------------------------------------------
figure('name','Power ihopsatt','NumberTitle','off')
    plot(tplot./(3600*24),Qheater2/1000,'color',[.5 .5
.5],'LineWidth',2);
```

```
    hold on

plot(tplot./(3600*24),Qheater_additional/1000*n_pipes+Qheater_tot_VP/
1000*n_pipes,'g','LineWidth',2);
    plot(tplot./(3600*24),Qheater_tot_VP/1000*n_pipes,'color', [1 0
0],'LineWidth',2);
    plot(tplot./(3600*24),Qheater_electric_VP/1000*n_pipes,'color',
[0.6 0.0 0],'LineWidth',2);

      plot(tplot./(3600*24),Qcooler2/1000,'color',[.5 .5
.5],'LineWidth',2);

plot(tplot./(3600*24),Qcooling_exchange/1000*n_pipes+Qcooling_additio
nal/1000*n_pipes,'g','LineWidth',2);

plot(tplot./(3600*24),Qcooling_exchange/1000*n_pipes,'b','LineWidth',
2);

    axis([ 0,max(tplot)/(3600*24) , floor(min(Qcooler2/1000)),
ceil(max(Qheater2/1000))])

    title('\fontsize{16}Distribution of total demand for climate
control')
    xlabel('\fontsize{12}Time for calculation [Days]')
    ylabel('\fontsize{12}Power [kW]')

        legend('Tot heating demand','Addtional heat',...
        'Heat from ground (HP)','Heat from electricity (HP)',...
        'Tot cooling demand','Additional cooling',...
        'Cooling from ground (Exchange)','location','SouthOutside')
%---------------------------------------------------------------------
 figure('name','MODE_nextsystemtemp','NumberTitle','off')
    plot(tplot./(3600*24),nextsystemtemp,'b','LineWidth',2);
    axis([ 0, max(tplot)/(3600*24) , -0.5, 1.5])
    title('\fontsize{16}Controlled by outlet temperature')
    xlabel('\fontsize{12}Time for calculation [Days]')
    ylabel('\fontsize{12}Control mode')
    legend('0=demands from building, 1=outlet
temperature','location', 'SouthOutside')
%---------------------------------------------------------------------
%DISPLAY SOME VALUES
%---------------------------------------------------------------------
if repetitions==0
Xar=(calculationtime/(8760*3600));
delar=1/(Xar);
    heatgroundKWH=(sum(Qheater_tot_VP)*time_stable/3600000*n_pipes);

coolgroundKWH=(sum(Qcooling_exchange)*time_stable/3600000*n_pipes);
heatgroundKWHyearochm2=heatgroundKWH/A_floors*delar;
coolgroundKWHyearochm2=coolgroundKWH/A_floors*delar;
disp('DEL FRÅN MARK')

disp([num2str(heatgroundKWH) ' kWh totalt under beräkningstiden
fixad(ej)='])

disp([num2str(coolgroundKWH) ' kWh totalt under beräkningstiden
fixad='])

disp([num2str(heatgroundKWHyearochm2) ' kWh/m2ochår till värme
fixad(ej)'])
```

```
disp([num2str(coolgroundKWHyearochm2) ' kWh/m2ochår till kyla
fixad'])

heat_of_total_demand=(sum(Qheater_tot_VP)*n_pipes)/sum(Qheater2);
cool_of_total_demand=(sum(Qcooling_exchange)*n_pipes)/sum(Qcooler2);
disp([num2str(heat_of_total_demand*100) ' % of total heating
demand'])
disp([num2str(cool_of_total_demand*100) ' % of total cooling
demand'])
if fixalast==1
if partoff<1
ground_of_modified_heat=sum(Qheater_tot_VP)*n_pipes/sum(Qheater2)
ground_of_modified_cool=sum(Qcooling_exchange)*n_pipes/sum(Qcooler2fi
xad)
elseif partoff>1
ground_of_modified_heat=(sum(Qheater_tot_VP)*n_pipes)/Qheater2fixad
ground_of_modified_cool=(sum(Qcooling_exchange)*n_pipes)/Qcooler2
end
disp([num2str(ground_of_modified_heat*100) ' % of modified heating
demand'])
disp([num2str(ground_of_modified_cool*100) ' % of modified cooling
demand'])
end
end
%--------------------------------------------------------------------
```