CHALMERS

House Inside a Glass House
-The Greenhouse Effect

Part II

Master of Science Thesis in the Master Programme Structural Engineering and Building Performance Design

Lena Wallin

Department of Civil and Environmental Engineering
Division of Building Technology
Building Physics
CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover:
The house inside the greenhouse in Vare. Photo: Lena Wallin

Chalmers reproservice
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ABSTRACT

Placing a building inside a greenhouse alters the climate surrounding the building. If the greenhouse can be used as patio this may extend the "outdoor" season. It may also be a way of saving heating energy. Measurements of the climates for a building standing inside a greenhouse outside Varberg have been made. For parameter studies of the climate in the greenhouse and the building a model was created in Simulink.

The greenhouse's temperature in respect to orientation, size, ventilation, internal sun screens and replacing the northern glass façade with a concrete wall was simulated.

The orientation and sun screens had almost no impact. The temperature, in general, increased with the greenhouse size. Sensor controlled ventilation cut off the heat peaks. The concrete façade heated the greenhouse, mainly during summer.

Five different building types were simulated: the original building with aerated concrete, a typical lightweight design and a typical heavy design and all three with $U_{wall} = 0.22$W/(m^2·K) and $U_{roof} = 0.21$W//(m^2·K), and two with higher U-values. For the first the aerated concrete was replaced by concrete with w/c 0.65 and for the second the insulation in the roof was removed. The thermal properties of floor construction, doors and windows were equal for all buildings.

The greenhouse proved to have a cooling effect of all of the three buildings with low U-values due to the reduction of solar radiation through the transmittance of the greenhouse glass. The original building was the warmest and therefore also the most energy efficient for heating. It was also the building least affected by the placement in the greenhouse. The lightweight structure was the most affected. Both buildings with higher U-values got heated by the greenhouse but not enough to compensate for the energy loss through transmission, when comparing to the original structure.

Key words: Building physics, greenhouse effect, energy efficiency, indoor temperature

Hus i Glashus - Växthuseffekten

Del II

Examensarbete inom mastersprogram konstruktion och byggnadsteknik
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SAMMANFATTNING

Om en byggnad placeras i ett växthus kommer den att omges av ett annat klimat än det som är utomhus. Förhoppningsvis kan detta klimat förlänga utomhussäsongen och minska byggnadens uppvärmningsbehov. För detta arbete har mätningar av temperatur och luftfuktighet gjorts för en byggnad i ett växthus uppförda utanför Varberg och för att kunna ändra parametrar skapades en modell av byggnaderna i Simulink. För växthuset simulerades temperatureffekterna av orientering, storlek, ventilation, solskydd med vävar och att ersätta den norra glasfasaden med en betongvägg.

Effekterna av rotering eller inre solskyddsvävar var små. Temperaturen ökade i huvudsak med storleken och sjönk med ventilationsgraden. Betongväggen ökade temperaturen i växthuset dock mest på sommaren.

Fem olika byggnadstyper simulerades. Originalbyggnaden med väggar av lättbetong, en typisk lätt konstruktion och en typisk tung konstruktion anpassades till att ha samma U-värden (U_{wall}= *0.22*W/(m^2·K) and U_{roof}=*0.21*W/(m^2·K)) därtill simulerades en byggnad där lättbetongen bytts ut mot en betong med vc-tal 0,65 och en där isoleringen på taket tagits bort.

Alla byggnaderna med de låga U-värdena kyldes av växthuset på grund av den minskade solinstrålningen. De andra två byggnaderna värmdes av den ökade omgivningstemperaturen. Dock var detta inte nog för att kompensera för de ökade transmissionsförlusterna som uppkommit genom de högre U-värdena. Originalbyggnaden var den varmaste och därmed även den som krävde minst energi för uppvärmning. Den var även den byggnad som påverkades minst av att placeras i växthuset. Den lätta konstruktionen påverkades mest.

Nyckelord: byggnadsfysik, växthuseffekt, energieffektivitet, inomhustemperatur

Contents

Preface

In this study, the effects on temperature and relative humidity of placing a building inside a greenhouse have been evaluated through measurement and simulations. The concept was designed by Mikael Frej and Klas Moberg at UNIT Arkitektur ab for a family living in the buildings (situated in Vare outside of Varberg, Sweden).

The measurements were started, by Louise Xu-Lilja, in January 2008 and terminated in December 2008. The simulations have been made in Simulink.

This work was initiated by the architects, desiring to get the concept evaluated, and carried out under the Division of Building Technology at Chalmers. Associate professor Angela Sasic Kalagasidis was supervisor and Professor Anker Nielsen responsible for the examination.

My warmest thanks to Angela, Klas and Mikael for the opportunity and for their help and patience. To Karin Sjödin with family for letting me into their house and to Louise who started the measurements for her work and thereby made it possible for me to obtain more values. To Wikström VVS-Kontroll AB for the disposal of measurement device and there especially to Stefan Wirtberg for his time. And last to Eline Geurts for her inspiring company.

Helsingborg January 2010

Lena Wallin

Notations

A	Area (m^2)
a	Thermal diffusivity (m^2/s)
c	Specific heat capacity (J/kg, K)
c_{pa}	Heat capacity of air at constant pressure (J/kg,K)
d	Thickness (m)
p_{sat}	Saturation pressure for the air (Pa)
T	Temperature (°C) (K)
t	Time (s)
U	Over all thermal transmittance (W/m^2,K)
V	Volume (m^3)
W	Heat load (W/s)
v	Vapor content (kg/m^3)

α	Angle of incidence
α_s	Surface heat transfer coefficient (W/m^2,K)
ρ	Density (kg/m^3)
φ	Relative humidity (-), (%)
λ	Thermal conductivity (W/m, K)
$c\rho$	Volumetric heat capacity (W/m^2, K)
τ	Transmittance (%)

Abbreviations

LW	Long wave
LSA	Lumped system analysis
RH	Relative humidity

1 Introduction

The possibility of creating a new climate zone within transparent walls is an idea brought to life in greenhouses and atria and, in more complex scale, sometimes used as a future vision in science fiction. The transparent walls create shelter from the outdoor environment at the same time as they permit possibility to see the screened environment, a sometimes appealing opportunity both from architectural and comfortable point of view. The possibility to let more daylight into the building may sometimes also be considered as an advantage, at least up here in the North.

This report studies a greenhouse enclosing a rather simple building with focus on the created climate in the greenhouse and in the building. The building is an extension of an older building and originally the family, that owns and lives in the building, had plans to build the extension as a more conventional room with "many windows" but discussions with UNIT Arkitektur AB ended with the greenhouse design. The main idea for this design is that the "outside" area in the greenhouse will function as a zone with a slightly warmer climate during the spring and autumn and therefore extend the outdoor period. Since there is also the possibility that the air in the greenhouse will have an insulating effect there was hope that this would be a possible way to construct energy efficient buildings with thinner walls and/or more windows, which would allow more daylight into the building. The building and the greenhouse are located in Vare, outside Varberg, Sweden. The arrangement of the buildings can be seen in Figure 1.1 below.

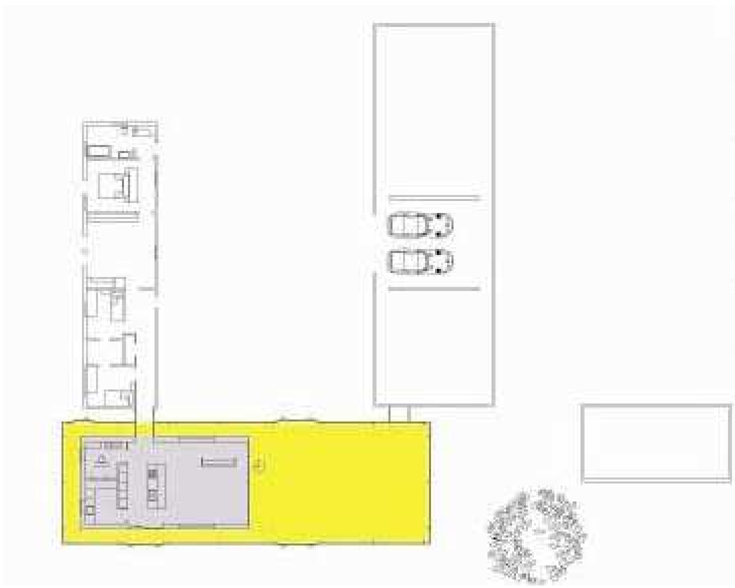


Figure 1.1 Arrangement of the buildings in Vare. The yellow area is the greenhouse.

1.1 Purpose

The main aims of this report are to present the climate in the greenhouse and the building and to examine the effects the greenhouse has on the climate in the building, both in climate and energy consumed for heating. This have been divided into four questions

1. What will the climates in the greenhouse and the building be?
2. What parameters affect the climate in the greenhouse?
3. How does the greenhouse affect the climate, and the energy consumption, in the building?
4. Would another type of building have been better to place in the greenhouse?

The main model is also compared to the results from a simulation with a model using Lumped System Analysis.

1.2 Method

To evaluate the climate in the greenhouse and the building measurements and simulations were used. The measurements were made to obtain values of the actual climate. The simulations made assessments of parameter changes possible, which would have been impractical or impossible to carry out on the site.

1.2.1 Measurements

The measurements were started by Louise Xu Lilja in late January 2008 and continued until the 1st of December that same year. Measured was;

- the air temperature and relative humidity outdoors
- the air temperature and relative humidity in the greenhouse
- the air temperature and relative humidity in the building
- the air temperature on the roof of the building

Though some of the measurements failed, and the RH outdoors was not measured from the end of April, they created a possibility to assess the climates in the greenhouse and the building, together with forming a basis for verifying the detailed simulation model. Since the period not cover a whole year standarized climate data for Göteborg was used for the simulations.

1.2.2 Simulations/ Parameter studies

For the simulations two Simulink models were constructed. The first was a simple model of the building based on Lumped System Analysis (LSA). This model was created both in order to be an introduction to Simulink and to give the opportunity of comparing LSA to the results of the other model. The second model was more detailed both concerning design and calculations. It contained both the greenhouse and the building and used modules from the International Building Physics Toolbox (IBPT). This model was used for the main part of the presented results since the LSA is less detailed and only gives the indoor temperature and the energy.

The input to the models was taken from drawings from Unit Arkitektur AB and Uno Borgstrand AB (the greenhouse manufacturer), information from manufacturers, tables of material properties and assumptions. Due to time limitations the aim was to find the behavior of the climate in the greenhouse and the building rather than to develop a perfect model and therefore some simplifications were made.

The energy demand was simulated for heating the building to 20°C during the heating period.

Below follows a description of the parameter study for the greenhouse and the building.

Greenhouse simulations

For the greenhouse the impact on the temperature was studied. This was made through changing parameters for;

- orientation
- size
- internal sun shading
- ventilation
- thermal mass

In addition to the changes in the temperature in the greenhouse was also the effect those temperatures had on the energy used for heating the building estimated.

Building simulations

For the building the effect of the greenhouse placement for five different designs was evaluated. The designs were;

- the original design
- a typical heavy design
- a typical light design,
- a very heavy design and
- the original design with the roof insulation removed

For all the buildings the indoor climate and the energy consumption were assessed. The first three buildings were constructed to have the same U-value and hence are also thermal effects of different designs with equal U-value discussed (chapter 11).

1.3 Limitations

Since the purpose was to evaluate the effect the greenhouse has on the climate in the building only a simple heating system, set to provide sufficient heating to keep the indoor temperature at 20°C during the heating period was modelled. The ventilation in the building was in most simulations set to have a constant air change rate of 0.5 air changes per hour, even though the family has the possibility to open windows and doors. The building is only cooled by ventilation, both in reality and in the model, so no estimations of energy needed for cooling have been made. Further on are the simulated values of the relative humidity very unsertain due to difficulties in finding proper input data for the outdoor relative humidity and the properties of the ground in the greenhouse, so focus is set on the temperatures and the values of the relative humidity in the model are mainly controlled so that they seem reasonable. No other size or shape of the building than the original is evaluated. The report is focused on the practical results and do not go into details about the theory behind them.

2 Description of the building and the greenhouse

Below follow descriptions of the constructed building and greenhouse. As mentioned in Section 1.2.2 some of the information is based upon assumptions. A number of contractors were hired and it was not considered valuable time spending to find the exact values since this will not affect the principal behavior of the building.

Both buildings are orientated with long sides facing North and South. The building is located in the Western part of the greenhouse and it occupies about 30% of the greenhouse's ground area, see Figure 1.1 in chapter 1. For the calculation of U-values 0.13 and 0.04m^2K/W were used as outer and inner surface resistance respectively.

2.1 The building

The building can be seen in Figure 2.1. It is a one-story rectangular building with an inner floor area of 63m^2 and an inner height of 2.4m. It contains a combined kitchen and living room, bathroom and a laundry room. The interior plan is visible in Figure 3.3. The building is connected to the old building through an open passage way of size 1.4x2.2m. The roof is planned to be used as a roof terrace.

Figure 2.1 Eastern and southern facades of the building

The materials in the envelope can be seen in Table 2.1. on the next page. Briefly; the foundation is an insulated concrete slab on the ground, the walls and the roof are constructed with aerated concrete and blocks of expanded clay respectively as load carrying elements and the doors facing the greenhouse (on the east and south walls) are sliding glass doors. The doors and the windows are assumed to have a U-value of 1.7 W/m^2, °C. The walls and the roof are lacking their finishing in the table, as they were in reality when the measurements were carried out.

Table 2.1 Materials in the building envelope

	d [mm]	λ [W/m, K]	ρ [kg/m³]	C [J/kg, K]	U [W/m²,°C]
Walls					0.23
Aerated concrete	375	0.09	375	1000	
Gypsum mortar	10	0.22	900	800	
Windows (2-glass)					1.7
Doors					1.7
Roof					0.18
Screed	30	1	-	-	
Insulation	150	0.033	14	800	
Blocks of expanded clay	250	0.3	1050	1000	
Floor					0.11
Screed	10	1.7	-	-	
Concrete	100	1.7	2300	30	
Insulation	300	0.033	900	800	

2.1.1 Heating and ventilation

The building is heated through the use of an air to earth heat pump (with electricity as back up source) connected to floor heating. The use of the heat pump creates an under pressure in the building which corresponds to an air change rate of 0.5 air changes per hour. The fresh air is taken in through ducts going under the ground from outside the greenhouse's East wall. When this ventilation rate is not enough the doors out to the greenhouse can be opened.

2.1.2 Internal loads

The family consists of two adults and three children. During the measuring period one of the parents was always at home with the children and they spent most of their time awake in the living room. The building contains the heat pump, washing machine, tumble dryer, double shower (toilet and washbasin), dishwasher, stove with oven and washing-up sink. The family chose not to participate with details of their daily routines considering creating internal loads.

2.2 The greenhouse

The greenhouse is a typical industrial greenhouse constructed by plain 4mm glass panes and aluminum frames. The manufacturer gives a U-value of about 7 W/m^2, K for the design. The ground area measures 25x8m and the ridge-height is 6.1 m. Doors are placed on the north and south facades (the northern also contains the opening for the passage way between the buildings). Figure 2.2 shows the southern façade and the greenhouse's location compared to the other buildings. Figure 2.3 shows the eastern façade.

Figure 2.2 The southern façade of the greenhouse.

Figure 2.3 The eastern façade of the greenhouse

The glass construction rests on plinths, raising the building 10-30cm, due to the inclination of the ground surface, above the ground. The space between the plinths is in its final form to be filled with stones and plastered. At the beginning of the measurements about half of the gaps were filled with larger stones, the rest were filled by the turn of February. According to Karin Sjödin the ground is old seabed consisting of about 80cm clay above sand. Inside the greenhouse the ground is first covered with a capillary breaking layer of gravel and then, to be finished, with a layer of clay tiles. The greenhouse is not used for growing, except for some tomato plants in pots, and rather serves as a patio than a regular greenhouse.

2.2.1 Heating and ventilation

The greenhouse is unheated. It is ventilated only through natural ventilation. The air intake and outflow is made through the leakages in the foundation and in the glass-aluminum construction and through the hatches placed on both sides of the ridge almost all along the greenhouse; see Figure 2.2 and Figure 2.3 above. The depth of the hatches is 900mm and the degree of opening is controlled by sensors feeling the temperature in the greenhouse together with wind speed and rain outdoors. The sensors were activated in the middle of August and the desired temperature in the greenhouse was then set to 20°C.

2.2.2 Sun shading

Woven sun screens are installed below the roof of the greenhouse, visible in Figure 2.1-2.3. They are manually adjusted and can cover the entire roof when so is desired. According to the manufacturer the screens transmit 83% of direct light and 75% of diffuse light. They are also supposed to hinder 47% of the energy from being radiated out of the greenhouse (Ludvig Svensson, 2008). The screens were installed in early June.

3 Measurements

Measurements were made from January 28 to December 1, 2008. The first part was made by Louise Xu Lilja (Xu Lilja, 2009). The equipment was borrowed from Wikström VVS kontroll AB and consisted of loggers for measuring and recording air temperature and relative humidity. The aim was to measure the climate outdoors, in the greenhouse and in the building. Partly to obtain figures over the climates and partly to obtain values to verify the climate model against. Due to a lack of experience and problems with the loggers some of the measurements failed. More details are presented in the section that follows.

3.1 Measuring periods and succeeded measured parameters

Xu Lilja measured from January 28 to April 26, 2008. The beginning of this period has to be considered a trial period since mistakes in the placements of the loggers were made. Also later some of the measuring points were a problem but then due to practical reasons. The placement affects the reliability of the results and the occurred problems are described and discussed later in this chapter. Problems with the functioning of the loggers made some measurements fail and therefore time periods and succeeded measured parameters are listed in Table 3.1.

Table 3.1 Measuring periods and measured parameters

		28/1-23/2	23/2-24/3	24/3-26/4	26/4-16/6	16/6-14/8	14/8-8/10	8/10-1/12
Outdoors	T_{out}	√	√	√	√	√		√
	RH_{out}	√		√				
Greenhouse	T_{low}	√	√	√		√	√	√
	T_{roof}			√	√	√	√	√
	RH_{low}	√			√	√	√	√
Building	T_{in}	√	√	√	√	√	√	
	RH_{in}	√	√	√	√	√	√	

Xu Lilja used periods of about 1 month while later the periods were extended in order to to reduce the time spent on travelling and the disturbance of the family. She recorded in intervals of between 15 min and 2h while for this thesis work only 30 minutes intervals were used.

3.2 Equipment

The measurements were made, depending on availability, either by SatelLite or by TinyTag. Both brands measure temperature or relative humidity (some devices of SatelLite measure both). The loggers were assumed to be calibrated by Wikströms, though when a small validation was made this showed differences of up to 0.5 degrees and 10 percent between the different loggers when measuring the same temperature or relative humidity respectively. For the temperature this is not considered to affect the conclusions while it for the relative humidity makes the results unsertain.

3.3 Measuring points

The measuring points had to be chosen due to the possibilities of placement and have therefore sometimes varied between the periods and not in all cases been good.

3.3.1 Measuring points for outdoor climate

The devices for measuring the outdoor temperature were placed in a cavity in the foundation to the greenhouse, about 20cm above the ground on the north façade. The measurements of the outdoor relative humidity were made from the same spot, except for the period 2008-02-23 to 2008-03-24 when the device was placed only 10cm above the ground and then broke due to moisture penetration. From April 26 the relative humidity outdoors has not been measured due to a combination of a misunderstanding and lack of equipment.

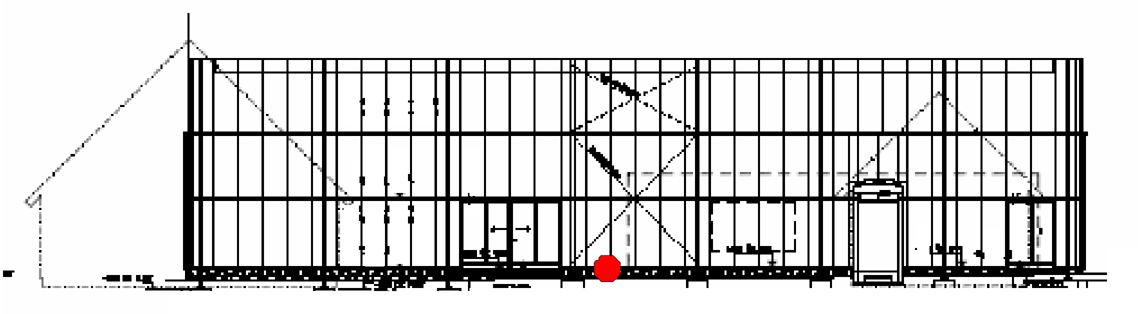


Figure 3.1 Measuring point for outdoor climate

3.3.2 Measuring points for climate in the greenhouse

The devices for measuring the climate in the greenhouse were initially mounted on a small tree almost in the middle of the greenhouse and about 1.2m up from the ground. To the second period the pot with the tree was removed and since then (end of February) the measurements had to be made from a spot about 30cm above the ground, 1m from the east wall and central in the north-south direction, see Figure 3.2. This is probably both too low and too close to the wall not to be affected by the moisture in the ground, the draught from the foundation and, most important, the sun from the wall.

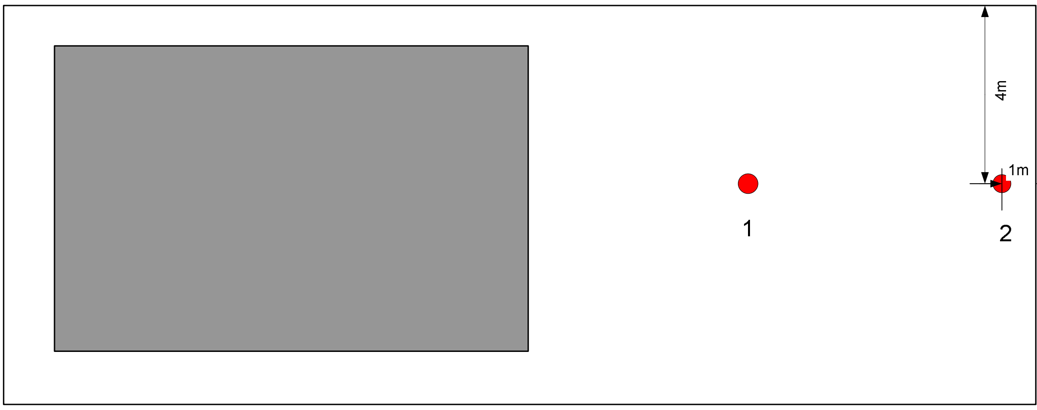


Figure 3.2 Placement of the loggers for measuring the climate in the volume of the greenhouse.

In addition to the attempt of measuring the climate in the volume of the greenhouse the temperature on the roof of the building was measured. This was made in order to see what the temperature on the planned roof terrace would be. Those measurements started with the third measurement period (end of March) and this device was from the beginning of August sheltered by aluminum foil to reflect direct solar radiation.

3.3.3 Measuring points for climate in the building

The measurements of the indoor climate were made with the devices taped to the legs of the dining table placed almost in the middle of the living room. This point is in the middle of the room and not exposed to direct solar radiation but it is only about 0.5 m above the floor that is a bit low. During the first period though the loggers were placed in the northern window. This gave cause to very distinct peaks when the solar radiation increased and low temperatures otherwise (and corresponding changes in relative humidity), clearly affected by the greenhouse temperature and solar radiation. Figure 3.3 shows the measuring points.

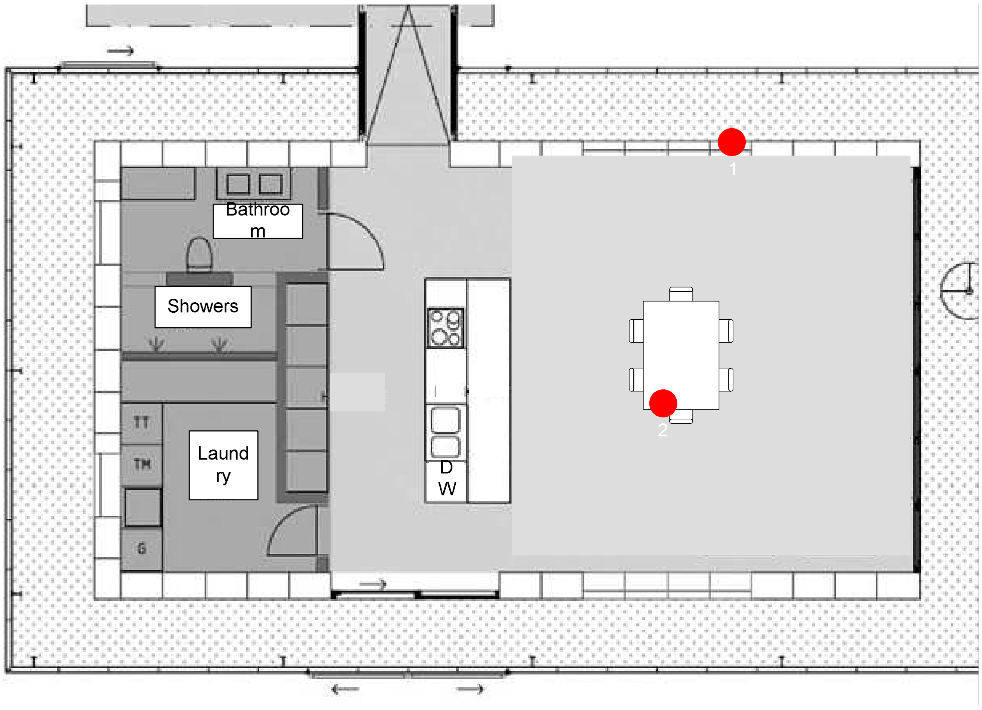


Figure 3.3 Measuring points for the climate in the building

3.4 Results of the measurements

Below are the results of the measurements presented. They are divided into chapters about the climate in the greenhouse and one about the climate in the building. Main focus is given to the temperatures, both since they are considered to be the most likely to cause discomfort and since the reliability of the measured relative humidity is low. The results from the measurements are not attached as an appendix but they are available on a CD stored at the Division of Building Technology.

3.4.1 The measured climate in the greenhouse

Due to the measurement point that was used (for all measurement periods except the first) the measured climate in the greenhouse is rather insecure and shall only be considered as indicative. Also that the fact that the prerequisites for the climate in the greenhouse changed during the measuring period had an impact on the possibility of assessing the climate in the completed greenhouse.

The disadvantages with the measuring point were; firstly that it was not in the area where people are and it therefore did not measured the climate sensed by the people. Secondly, the closeness to the eastern façade (about 1m) made it very likely for the results to be directly affected by the intensity of the solar radiation and therefore overestimate the temperatures during warmer days. This gives reason to believe that the temperature results for the winter, when the solar radiation is low, are more reliable than those for the summer. Thirdly, the closeness to the façade in combination with the low placement, about 30cm above the ground, make the measured impact of ventilation unsertain since this is not in the main volume of the greenhouse, where most of the air movements take place. Fourthly, the low placement also made it probable that the loggers for RH were affected by the moisture from the ground.

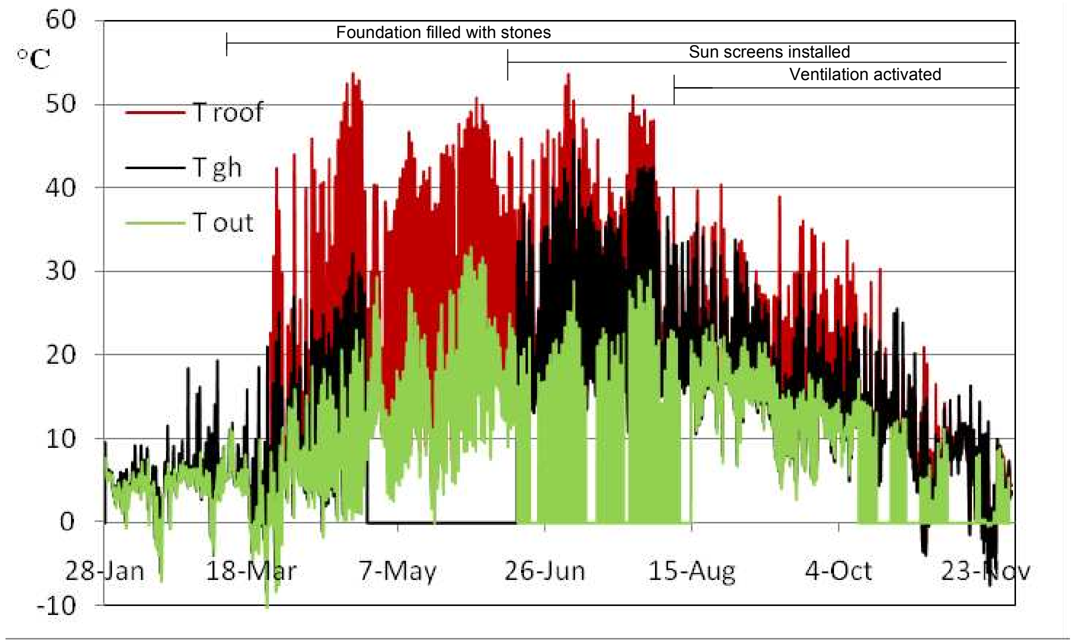
The logger on the roof of the building was not protected from direct sun radiation until the middle of August.

About the prerequisites for the greenhouse it can again be said that the greenhouse was not completed in the sense of tightness, ventilation and sun screening when the measurements started. The foundation was filled with stones by the turn of February, the sunscreens were installed in early June and the ventilation activated in the middle of August.

Keeping those faults in mind the results of the measured climate in the greenhouse is presented below, first the temperature and then the relative humidity.

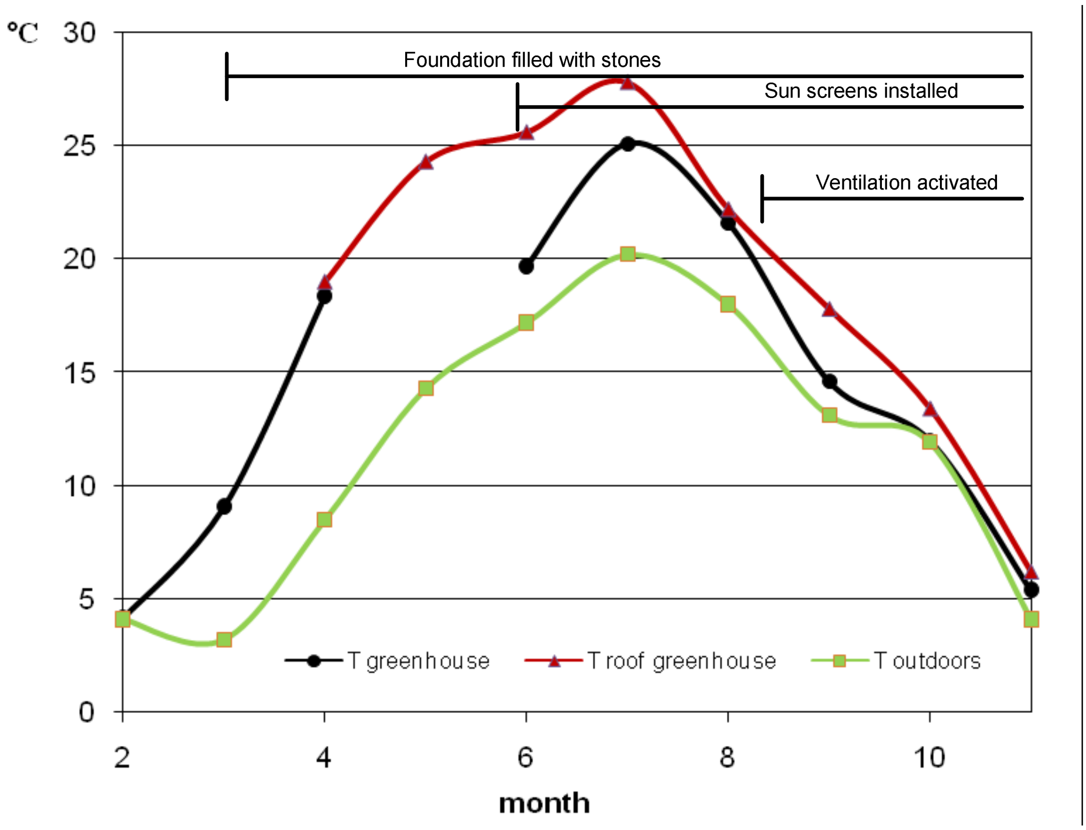
3.4.1.1 Results of measured temperatures in the greenhouse

Figure 3.4 below shows the measured temperatures in the greenhouse and outdoors, a) as they were measured over the period, b) as monthly mean temperatures and last in c) in a duration diagram. For the periods when the measurements of the outdoor temperature failed (appear as zero values in Figure 3.4a), the temperature at 12 am, for each available day, have been taken from measurements made by Varberg Energi (www.temperatur.nu, 2008). From their web page also the monthly mean temperatures for the missing months were taken.



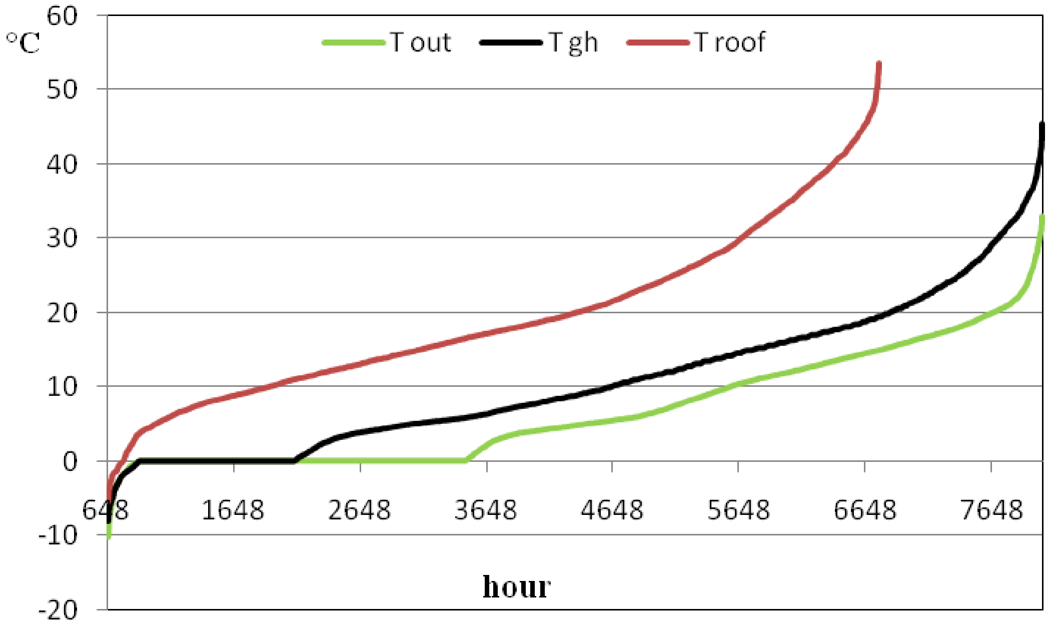
60
°C
50
40
30
20
10
0
-10
Foundation filled with stones
Sun screens installed
Ventilation activated
T roof
T gh
T out
28-Jan
18-Mar
7-May
26-Jun
15-Aug
4-Oct
23-Nov

a)



°C
30
25
20
15
10
5
0
Foundation filled with stones
Sun screens installed
Ventilation activated
T greenhouse
T roof greenhouse
T outdoors
2
4
6
8
10
month

b)



c)

Figure 3.4 Measured temperatures in the greenhouse and outdoors from January 28 to December 1. a) the measured temperatures in the greenhouse and outdoors b) monthly mean temperatures c) duration diagram

Figure 3.4 shows that even if the error connected to the measurement points is unknown the general behavior of the temperatures is the expected. The temperatures in the greenhouse are higher than the outdoor temperature and this difference increases with the outdoor temperature (i.e. with the intensity of the solar radiation). Further on the temperature on the roof is warmer than the temperature close to the ground. The lack of measured values is visible in the duration diagram as the long periods with a temperature of zero degrees. This affects the slope of the curves but not the conclusions.

3.4.1.2 Impact of solar shading and ventilation

In Figure 3.4 a) and c) it can be seen that the measured temperatures in the greenhouse are well above 40 degrees (above 50°C for the roof) during some warm days. Those temperatures were measured before the ventilation hatches were activated and the greenhouse was then only ventilated through the doors, the leakages in the foundation and a broken pane in the roof. The sun screens on the other hand, were installed just before the highest greenhouse temperatures were measured. Taking a look at the measured temperature on the roof of the building in a), since those measurements succeeded also for the period before, it can be seen that the sunscreens not seem to have any impact on the temperature. The temperature on the roof remains unchanged high compared to the previous period, even though the outdoor temperatures then were higher. Also the results from simulations, Section 7.5, show a very little impact of the screens. In that chapter an explanation for this is given.

When the ventilation was activated (see Figure 3.4 a) and b)) a clear difference for the roof temperature can be seen. There can be two reasons for this; either that the logger was protected from direct solar radiation or the effect of the activated ventilation. The logger was partly protected also by the screens, and this had no visible impact, and hence the result is most likely to be due to the ventilation.

For the lower measurement point there is a difficulty to see any difference in the temperature, though the family's experience of the activation is that the temperature got more comfortable. The low impact may be due to the impact of the closeness to the façade or that the low placement close to the edge of the greenhouse not is where the major circulation occurs.

3.4.1.3 Impact of solar radiation on the temperature differences between the outdoor temperature and the greenhouse temperature

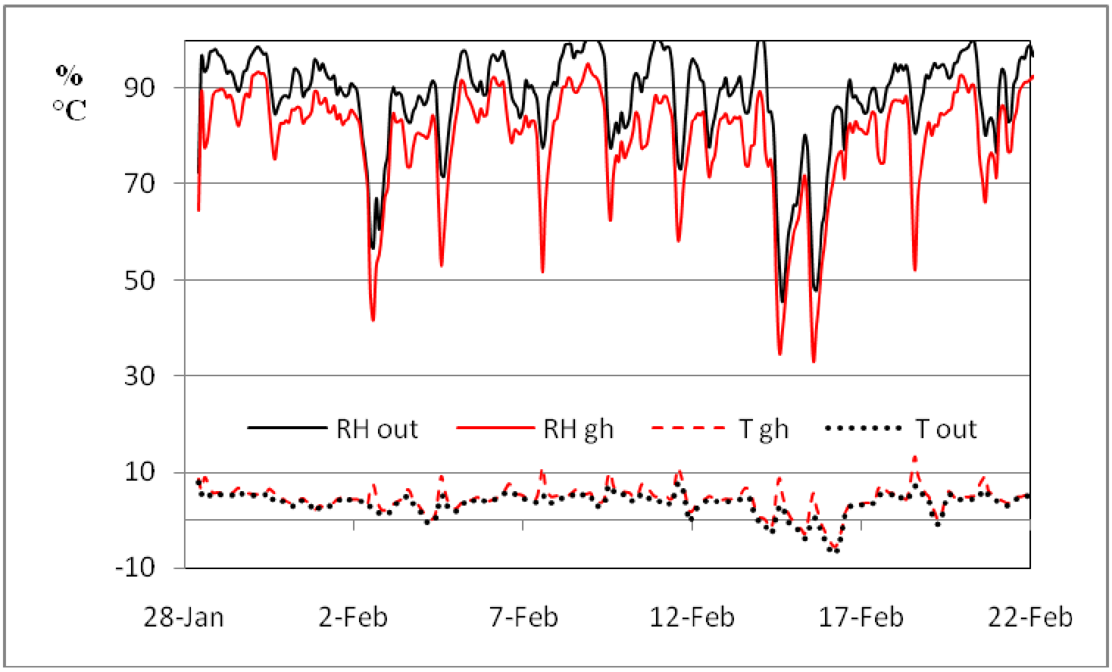
Unfortunately the measurements of both greenhouse temperature and outdoor temperature have not succeeded for one warm and one cold period with the loggers inside the greenhouse on the low spot, which makes it impossible to assess the impact of the bad placement.

3.4.1.4 Relative humidity and vapor content

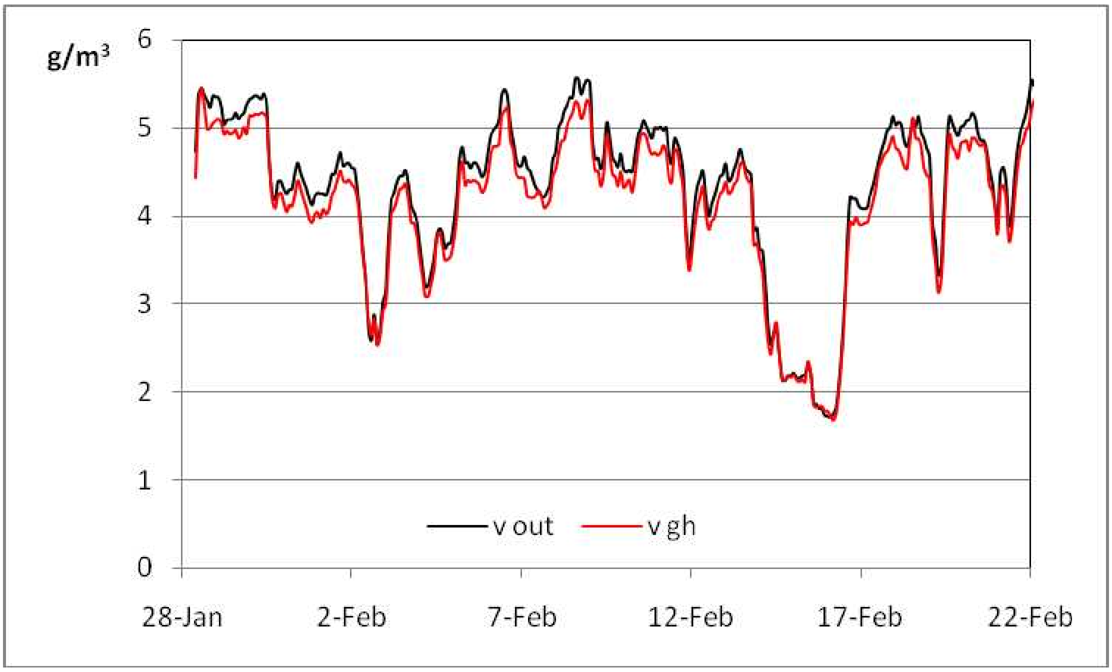
Since there only is one period with measurements of both the relative humidity outdoors and in the greenhouse this section first contains a comparison between the humidity in the greenhouse and outdoors and then the rest of the results from the measured humidity in the greenhouse are presented.

3.4.1.5 Comparison between the climate outdoors and in the greenhouse

Figure 3.5 shows the differences between the climate outdoors and in the greenhouse, in a) as a comparison between relative humidity and temperatures and in b) as a comparison of the vapor content in the air.



a)



b)

Figure 3.5 a) Relative humidity and temperatures in the greenhouse and outdoors from January 28 to February 22 b) Vapour content in the air in the greenhouse and outdoors from January 28 to February 22

In a) it can be seen that that the relative humidity in the greenhouse is lower than outdoors and that this is the result of the higher temperature. In b) one more reason for the difference in RH can be seen and that is that the vapour content in the greenhouse in general is a little lower than outdoors. The difference in vapour content seems to increase with the outdoor temperature, which is an effect of the ground drying out during the warm season. The vapour content in the air was calculated from the measured RH and temperatures using equation 3.1 and 3.2 below. The equation for the saturation pressure is from Hens, 1996.

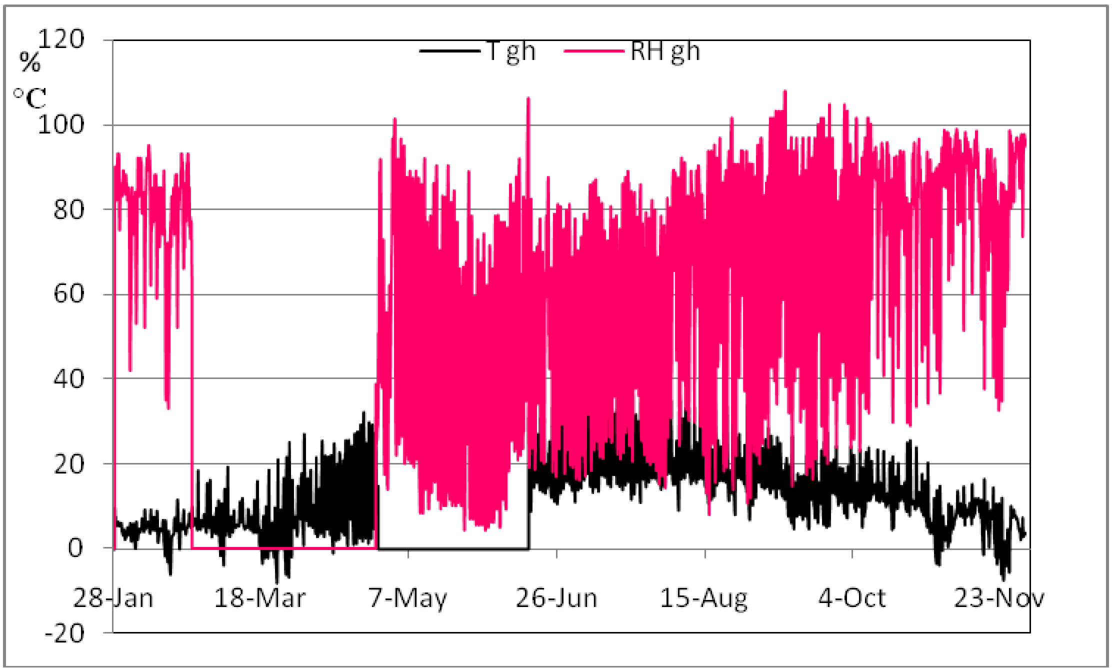
$$v = \frac{\varphi \times p_{sat} \times 0.621 \times 1000}{101325 - \varphi \times p_{sat}} \qquad (3.1)$$

Where

$$p_{sat} = \exp(23.5771 - \frac{4042.9}{T - 37.58}) \qquad (3.2)$$

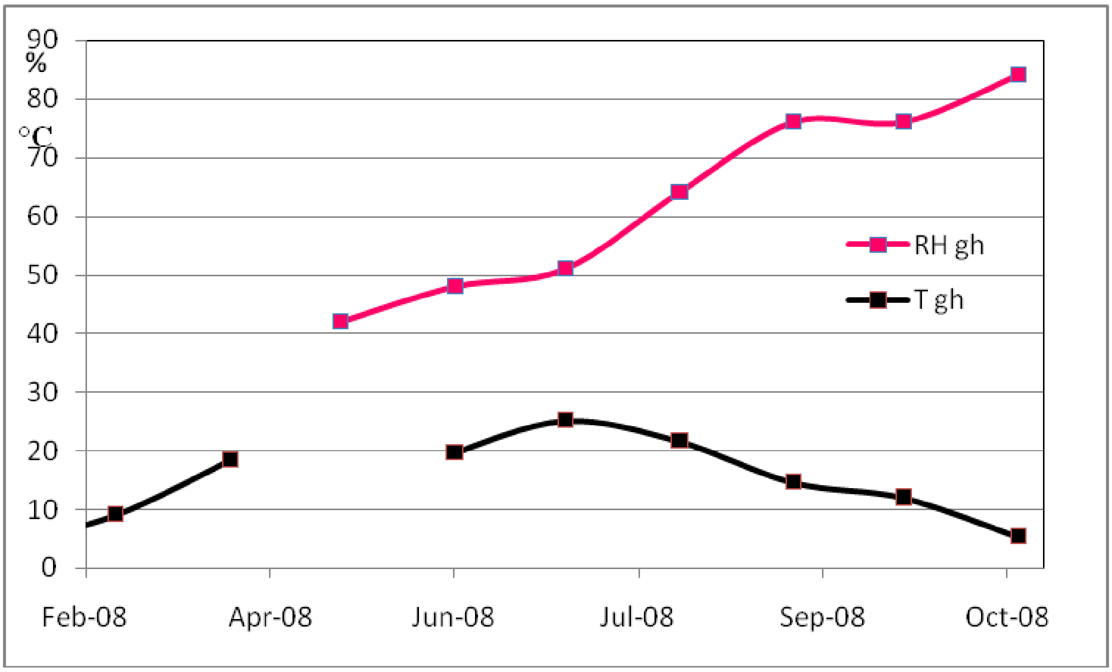
3.4.1.6 Relative humidity and vapour content in the greenhouse

In Figure 3.6 the measured relative humidity in the greenhouse can be seen over the entire measurement period. In a) is the measured relative humidity in the greenhouse and the temperatures in the greenhouse and outdoors from January 28 to December 1 shown, in b) the monthly mean values for the relative humidity and the temperature in the greenhouse from February to November and in c) is the monthly mean vapor content shown.



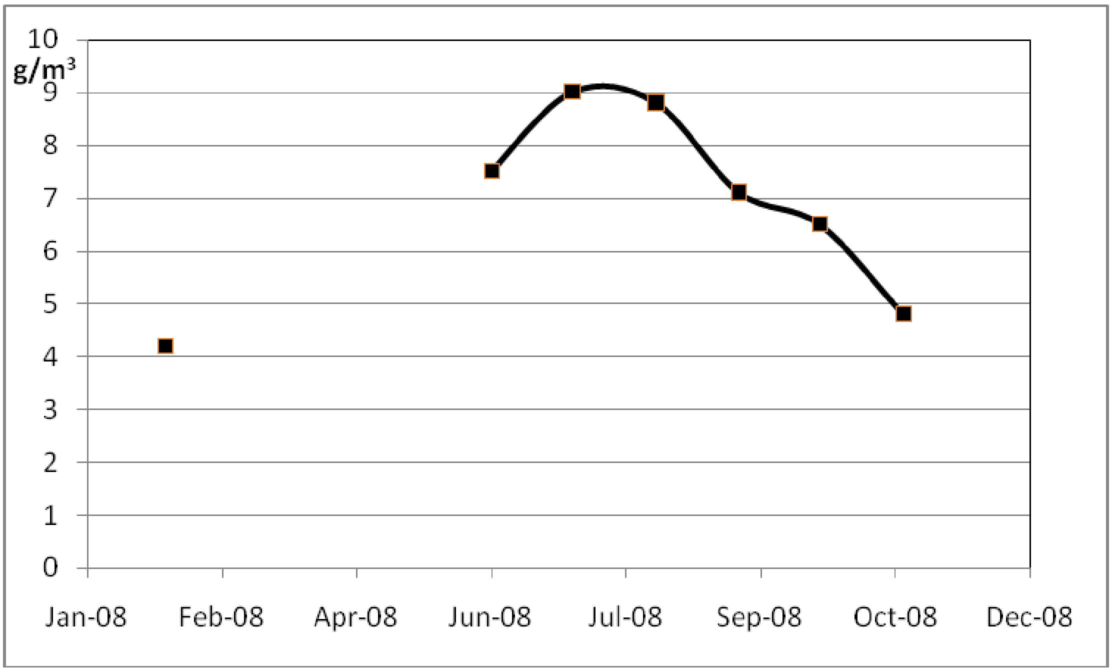
%
°C
120
100
80
60
40
20
0
-20
T gh
RH gh
28-Jan
18-Mar
7-May
26-Jun
15-Aug
4-Oct
23-Nov

a)



%
°C
90
80
70
60
50
40
30
20
10
0
RH gh
T gh
Feb-08
Apr-08
Jun-08
Jul-08
Sep-08
Oct-08

b)



c)

Figure 3.6 a) Measured relative humidity in the greenhouse and temperatures in the greenhouse and outdoors from January 28 to December 1 b) monthly mean RH and temperature c) monthly mean values of the vapor content in the greenhouse.

Figure 3.6 a) shows that the RH varied from less than 10% up to condensation. Naturally the relative humidity never exceeds 100% in reality. The RH measurements, as mentioned before, are uncertain due both to the difference between the loggers, the closeness to the ground and the closeness to the wall. Remembering the very small difference in vapor content between the outdoor air and the air in the greenhouse and taking a look at the values for monthly mean vapor content c) the closeness to the ground appears not to be a problem from humidity aspect. The greenhouse is not very humid and more affected by the outdoor air than the ground. The very low RH values during summer are therefore likely to be a result of overestimated temperature due to the closeness of the wall and the capillary breaking gravel.

In order to easier assess the difference between the climate outdoors and in the greenhouse the monthly mean values have been gathered in Table 3.2 below (the temperatures and vapor content are the same as in Figure 3.5 b) and 3.6 c) respectively). The ‘ indicates that there were not measured values for the entire month and therefore is the value the mean value of day 1-26 for April and day 16-30 for June. The * indicates the use of temperatures measured by Varberg Energi.

Table 3.2 Measured monthly mean humidity and temperature

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
RH_{gh} [%]		61	-	-	42	48	51	64	76	76	84	
T_{gh} [°C]		4.2	9.1	18.4’	-	19.7’	25.1	21.6	14.6	12.0	5.4	
$T_{gh,roof}$ [°C]				19.0	24.3	25.6	27.8	22.2	17.8	13.4	6.2	
T_{out}		4.1	3.2	8.5	14.3	17.2*	20.2*	18*	13.1	11.9*	4.1*	

[°C]		4.0*	3.1*	8.2*	14.0*				12.0*			
v_{gh} [g/m^3]		4.2				7.5’	9	8.8	7.1	6.5	4.8	
v_{out} [g/m^3]		4.4										

Assuming the relative humidity to be equal in the entire greenhouse and the measurements on the roof to be reliable the climate on the roof of the building appear to be close to the climate in Seville in Spain, see Figure 3.7. The climate in the volume of the greenhouse is most likely a little bit colder. From Figure 3.4 it can be seen that (at least at some spots) the temperature in the greenhouse can be above 18 from February to the end of October compared to the outdoor season more general is from middle of March to the beginning of October. The Seville climate is taken from Meteonorm.

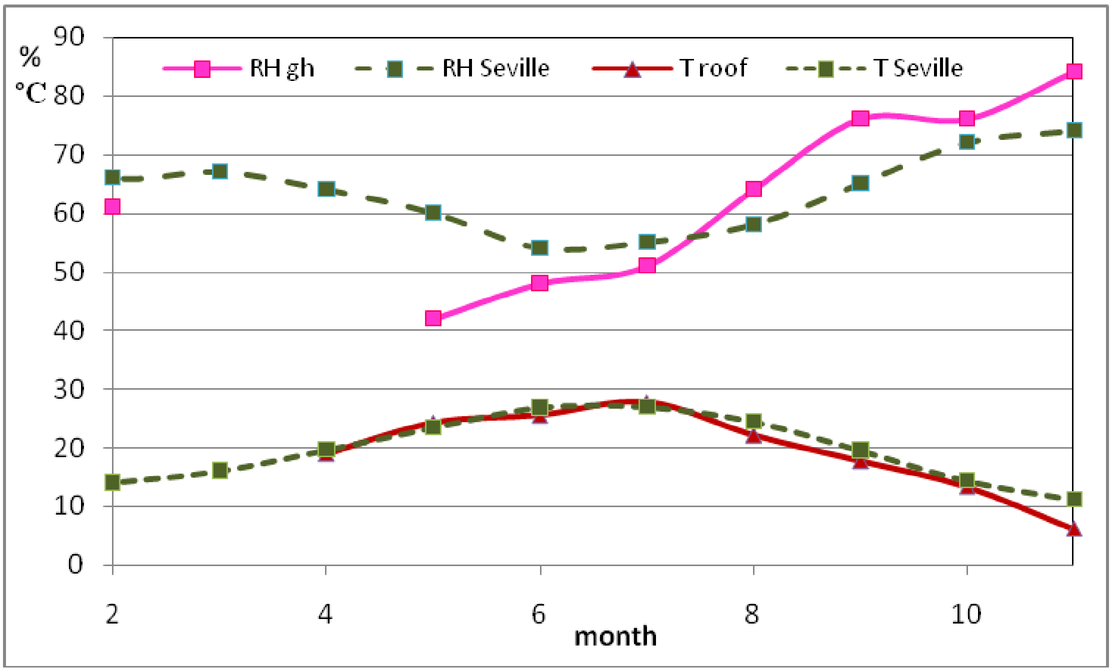


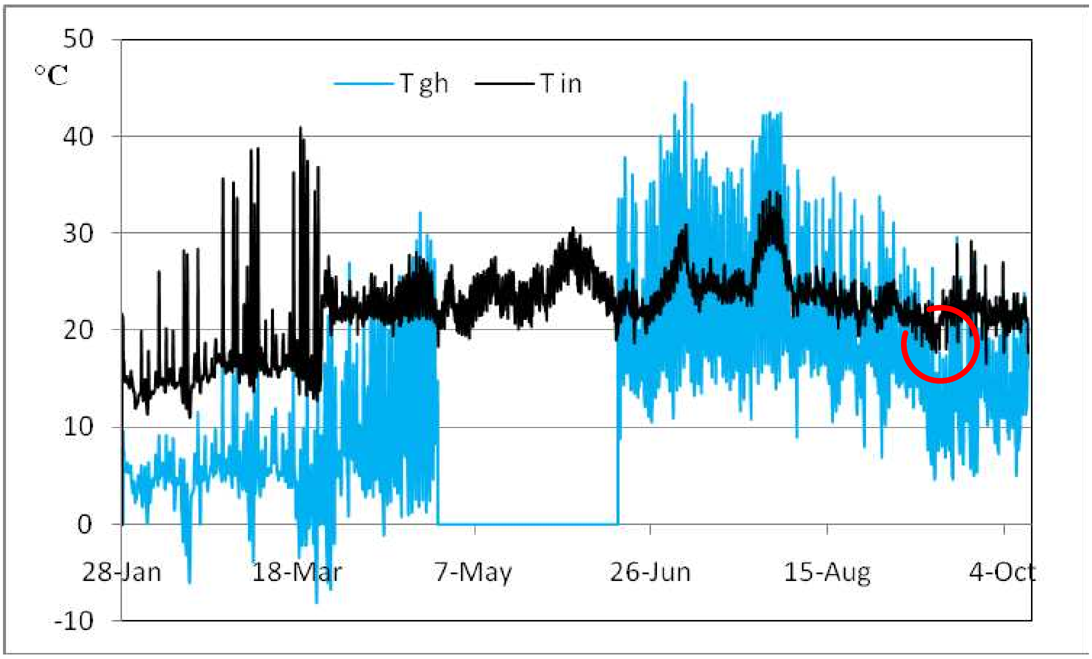
Figure 3.7 Monthly mean values for the climates in the greenhouse and Seville.

3.4.2 The measured climate in the building

Since the last period failed measured values of the climate in the building were obtained from January 28 to October 10. From the beginning until March 24 the loggers were placed in the northern window and the results from those measurements are included in Figure 3.8 a) and 3.9 a) only to show the difference in climate between this location and the center of the room. The other measurements were made from the table leg. Unfortunately there are no values from this point for cold outdoor temperatures. The building was occupied during the whole measurement period and therefore ventilated both by the ventilation system and opening of doors.

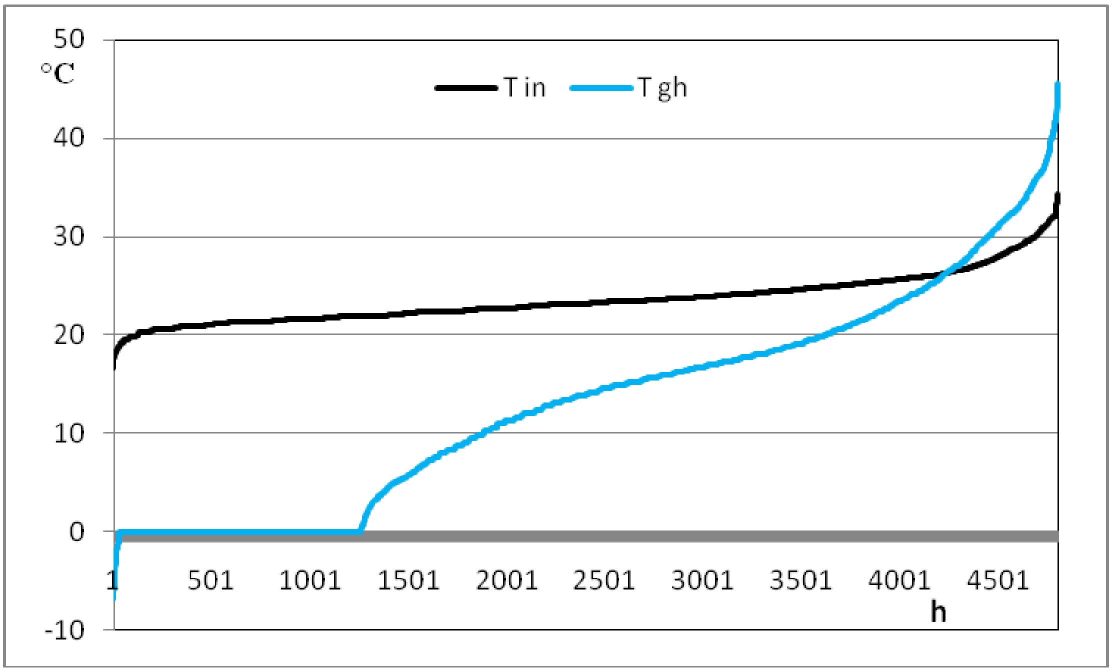
3.4.2.1 The measured temperature in the building

Figure 3.8 below shows the temperature in the building compared to the temperature in the greenhouse in a) as the measured temperatures over the period, in b) as the monthly mean temperatures from March to September and in c) in a duration diagram (window temperatures not included).



a)

b)



c)

Figure 3.8 a) The measured temperature in the building and the greenhouse. b) Monthly mean temperatures from March to September. c) Duration diagram over the temperatures from March 24 to October 10

Figure 3.8 a) shows that the temperature fluctuations close to the window are a lot higher than for the point in the middle of the room. The temperature in the window is easier affected by the intensity of the solar radiation and the temperature in the greenhouse than the temperature in the middle of the room.

From Figure 3.8 a) and b) it can be seen that the temperature indoors follows the trends for the temperature in the greenhouse. The temperature in the building is also affected by the solar radiation but since it contains less glass areas the effect is not as fluctuating as for the greenhouse. The smaller glass areas combined with the insulation of the building, which prevents the indoor temperature from falling quickly when the greenhouse temperature drops, results in a more stable climate in the building. The result is an average temperature above the greenhouse's, also during the months when no heating is needed. For numerals see Table 3.3.

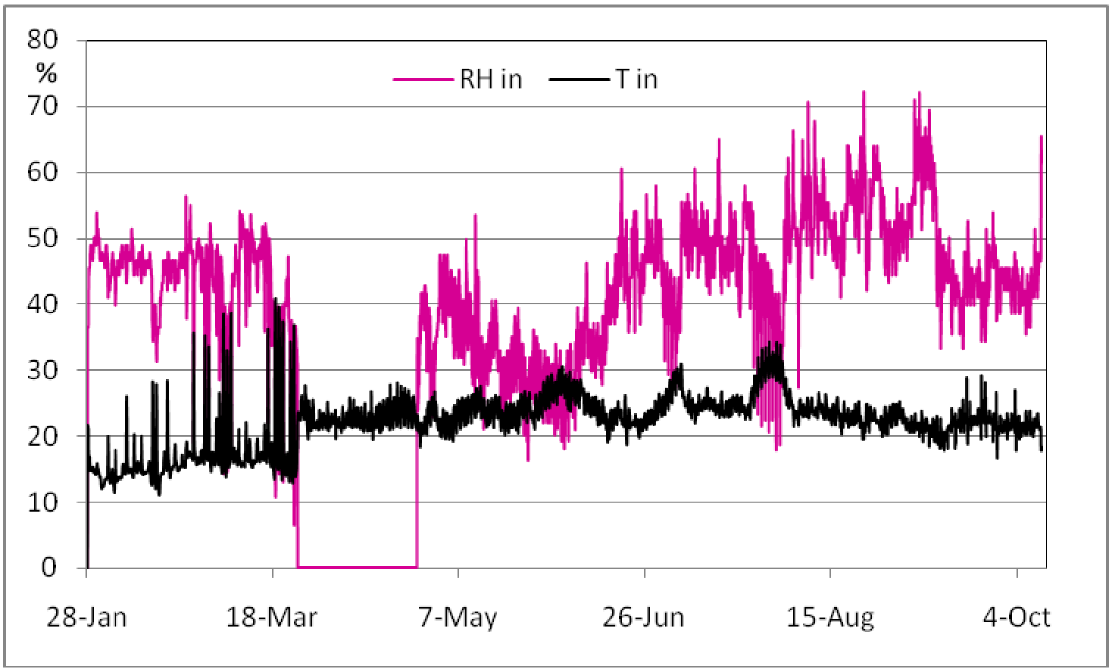
The duration diagram, Figure 3.8 c), shows that the indoor temperature during the measured time mainly was comfortable. The temperature fell below 20°C a couple of times, (with a minimum of 16.7°C) which for the single values may have been caused by the opening or improper closing of the glass doors when entering or leaving the building through the greenhouse. The longer duration of colder indoor climate, the red circle in a), may indicate a problem with the heating but it may also be the result of too late switching on the heating. The heating seems not to be a problem during the rest of the measurements. For most of the time though the indoor temperature was high. About 10% of the time the temperature was above 27°C with a maximum of 34.3°C. As mentioned above this is a result of the building being rather well insulated and affected by the solar radiation. This is further discussed in chapter 8.

Table 3.3 Monthly mean temperatures in the building and the greenhouse

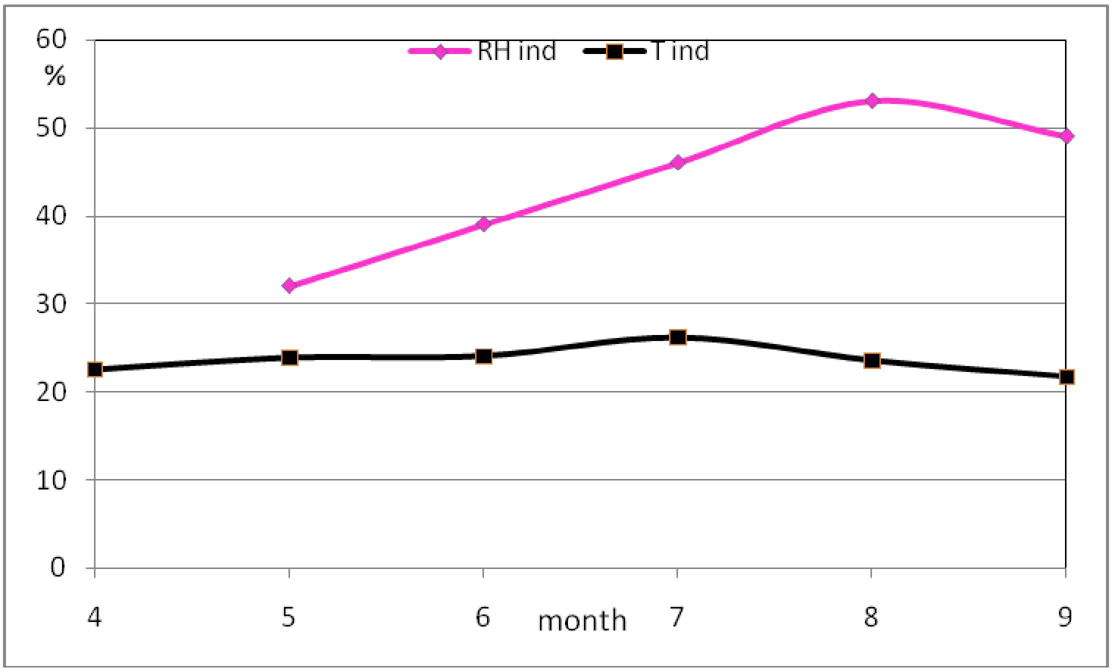
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept
Greenhouse [°C]		4.2	9.1	18.4		19.7	25.1	21.6	14.6
Indoors [°C]				22.6	23.9	24.1	26.2	23.6	21.8

3.4.2.2 Measured relative humidity in the building

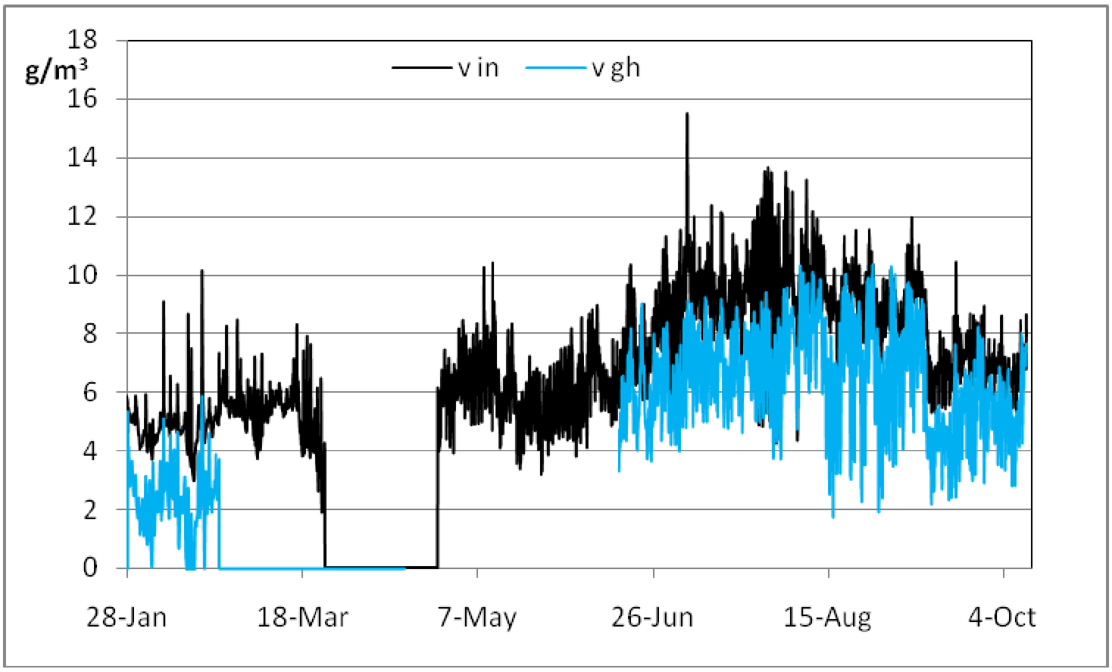
The measured humidity in the building is shown in Figure 3.9 below. In a) as the relative humidity together with the indoor temperature over the period, in b) as the monthly mean values from April to September and in c) is the vapor content in the building and the greenhouse shown.



a)



b)



c)

Figure 3.9 Humidity in the building. a) Relative humidity and temperature in the building from January 28 to October 10. b) Monthly mean values for the relative humidity and the temperature in the building from April to September. c) Vapor content in the indoor and greenhouse air from January 28 to October 10.

Figure 3.9 a) shows that when the temperature in the building rises high and the relative humidity falls well below the recommended minimum level of 30% (Socialstyrelsen, 2009). This may cause some discomfort but since the mean relative humidity stays between the recommended 30-70% for the measured time, b), this is not likely to be a health problem. In contrary it may even have a positive effect on the experienced climate in the building during the warmest hours since the dry indoor climate makes water evaporate from the skin, which has a cooling effect, and the fact that a warm and dry climate often is perceived more comfortable than a warm and humid climate.

The increase of relative humidity during the autumn follows with the increase in vapor content, c) and Table 3.4, and is likely to be due to the moisture buffering effect of the materials and the ground in the greenhouse. The vapor content in the air increases during the summer (even though the relative humidity decreases due to the higher temperatures). The vapor gets stored in the materials and the ground and when the vapor content in the air falls the stored moisture/water is released into the air again. This is further explained in chapter 9.

Table 3.4 Monthly mean vapor content in the greenhouse and in the building

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept
Greenhouse [^{o}C]		4.2				7.5’	9	8.8	7.1
Indoors [^{o}C]		4.8	5.1	5.4	3			6.5	5.5

3.5 Main conclusions from the measurements

During the summer the temperatures rise high both in the building and in the greenhouse. For controlling the temperature in the greenhouse the sunscreens seem to have no impact on the temperature while the effect of the ventilation is clearly visible. The relative humidity in the building is sometimes very low but this is over all not a problem.

4 Descriptions of the models

Two models have been created. The first is a simpler model using Lumped System Analysis (LSA) to estimate the indoor temperature in the building, not considering moisture. The second, the main model, is a detailed model for simulating the climate in the greenhouse and the building. Both models were created in MatLab based Simulink. The LSA model was made using the Simulink blocks while the detailed model used blocks from International Simulink Building Physics Toolbox (ISBPT). Those blocks (using the Simulink blocks) were developed by Building Physics Department from Chalmers University of Technology, Sweden, and the Department of Civil Engineering from Technical University of Denmark. (IBPT, 2006) The use of the pre developed blocks allowed the creation of a model more detailed than what otherwise would have been reasonable due to time consumption and programming skills.

Both models are used to find the numerical solutions to equation 4.1

$$\rho_a c_{pa} V \frac{dT_{in}(t)}{dt} = UA[T_{ut} - T_{in}(t)] + \frac{nV\rho_a c_{pa}}{3600}[T_{vent} - T_{in}(t)] + A_{win}\left[\tau(\alpha) I_{dir} + \tau_{diff} I_{diff}\right] + W_{int} \tag{4.1}$$

The expression on the left hand side describes the change in stored heat while the expressions on the right hand side describes the transmission losses, ventilation losses, gains from solar radiation through windows and the internal gains respectively. Note that the transmission and ventilation losses, take the colder temperature subtracted with the warmer and that these two terms therefore in practice are negative (when heating). (Hagentoft, 2001)

The models are presented below and since the climate model is the most advanced the areas and material properties used in the models are listed in chapter *4.2 Detailed model*. The LSA model uses the same values for the parameters it requires. The U-values are calculated by hand using the standard value 0.13m^{2}K/W as outer surface resistance.

4.1 The Lumped System Analysis model.

Lumped System Analysis (LSA) is based on the assumption that the building is that well insulated that the indoor temperature is constant even a (short) distance into the building envelope (in comparison to "normal" calculations where the inner wall and the indoor air are considered to have different temperatures and therefore give cause to an energy transfer between the wall surface and the air). This assumption simplifies the calculations in such ways that the inner surface resistance can be neglected and all the volumetric heat capacities inside this distance (e.g. the parts of the walls with the same temperature as the indoor temperature, partition walls, furniture and the indoor air) can be added together, to form Ctot. The LSA transmission losses are then calculated from the points in the envelope where the temperature starts to differ from the indoor temperature out to the surrounding outdoor air. See Figure 4.1 for clarification with a simple wall example.

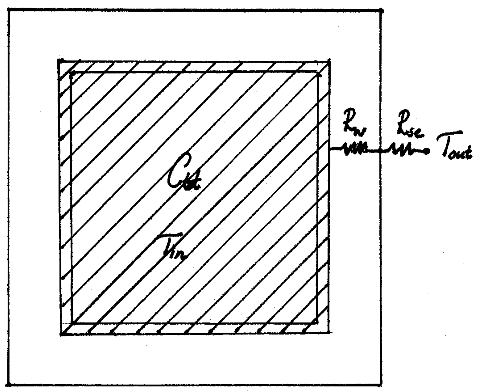


Figure 4.1 C_{tot} and resistances for a wall calculated with Lumped System Analysis.

When LSA is used, Equation 4.1 becomes simplified to

$$C_{tot}\frac{dT_{in}(t)}{dt} = K_{tot}\left[T_{ut} - T_{in}(t)\right] + \frac{nV\rho_a c_{pa}}{3600}\left[T_{vent} - T_{in}(t)\right] + A_{win}\left[\tau(\alpha)I_{dir} + \tau_{diff}I_{diff}\right]W_{int}$$

(4.2)

Where

$$C_{tot} = \sum_i \rho_i c_i V_i$$

$$K_{tot} = \sum K_{part}$$

$$K_{part} = A_{part,j}\frac{1}{R_{se,j} + R_{w,j}}$$

The index *i* denotes the different materials holding the indoor temperature, *j* the different building parts (walls, roof etc) and *w*, only because a wall is chosen in the Figure, represents the resistance of the materials in the building part.

In the model is the greenhouse (e.g. the air in the greenhouse) assumed to work as the thick layer of insulation around the building that enables the LSA. Therefore were the simulations made with the surrounding temperature being the outdoor temperature, and no simulation for the building alone was possible. The ventilation was assumed to have an air change rate of 0.5.

The penetration depths of the indoor temperature into the envelope were calculated as the depth for heat penetration after 24h (standard period since the temperatures seldom is “constant” longer than a day), according to equation 4.3 (Hagentoft, 2001).

$$d_p = \sqrt{\frac{at_p}{\pi}} \qquad \text{[m]} \qquad (4.3)$$

Where

$$a = \frac{\lambda}{\rho c} \qquad [m/s]$$

The model also includes solar radiation through glass areas where the transmittance is set to be constant both for direct and diffuse light, 0.68 for the windows and 0.66 for the doors and internal heat loads as presented in next section.

4.2 Detailed Model

This model aims to give a better solution to equation 4.1, and corresponding equation for moisture, through splitting the material layers and the air into a number of elements and calculate the temperature and moisture content in each of those.

For more information about the IBPT please see *www.ibpt.org*.

The model itself can be separated into two models where the first contains only the building and the second contains the building placed in the greenhouse. The model of the building alone is used as reference when effect of the greenhouse is studied. In the model with the building placed in the greenhouse is not the effect the building has on the greenhouse climate simulated. Therefore this model was also used to simulate the climate in the greenhouse alone.

In the following to chapters are the input data for the models presented.

4.3 Input data for the modeled buildings

In this chapter the areas, materials and transfer coefficients used in the models are presented, firstly the building and then the greenhouse. Necessary comments to the chosen parameters and deviations between the models are given below each table.

4.3.1 Input data for the building

Table 4.1 Surface areas

	North		East		South			West		Roof	Floor
	Wall	Win	Wall	Win/door	Wall	Win	Door	Wall	Win		
A [m^2]	34.8	3.4	7.2	14.0	30.0	3.4	4.8	19.4	1.8	76.4	76.4

In order to compensate for the loss through cold bridges the wall measures are outside measures. The windows and glass doors are assumed to consist of two glass panes separated by an air gap, no frames. Further is the opening for the passage way over to the old building ignored and this area is handled as wall.

With no consideration taken to partition walls and furniture the internal volume in the building is 151 m^3 which is the value used in the simulations.

Table 4.2 Materials and their thickness and properties in the modeled building

Part	Material	d [mm]	λ [W/m,K]	ρ [kg/m3]	c [J/kg,K]
Walls	Aerated concrete	375	0.09	400	900
	Gypsum board	10	0.2	700	870
Roof	Concrete w/c ratio 0.65	30	1.5	2400	800
	Mineral wool	150	0.04	14	800
	Blocks of expanded clay	250	0.3	1050	1000
Windows and doors 2 glass	Glass	3	1.06		
	Air gap	10	0.025	1.2	1000
Floor	Expanded polystyrene	300	0.03	20	1400
	Concrete w/c ratio 0.65	100	1.5	2400	800
	Concrete w/c ratio 0.65	15	1.5	2400	800

The properties for the aerated concrete and the blocks of expanded clay were obtained from the manufacturers. The other materials and their parameters were taken from the pre made library in IBPT. In the model the gypsum plaster on the original walls is replaced with gypsum board, the screed on the floor is replaced by regular concrete and loose fill insulation is used on the roof. Those material changes are due to what was obtainable in the library and the two first seem to be minor changes but the use of loose fill insulation has probably underestimated the volumetric heat capacity and overestimated the lambda value, and thereby lead to overestimated transmission losses.

Table 4.4 Transmittance for solar radiation for the windows

	Diffuse	Direct					
α [°]		0	40	50	60	70	80
τ	0.65	0.75	0.73	0.70	0.63	0.49	0.49

The building can be set to be ventilated with 0.5 air changes per hour, irrespective of the indoor temperature or with an increasing number of air changes per hour due to indoor temperature simulating the effects of opening the doors to the greenhouse. The modeled building is cooled only through the ventilation, just as the original. The heating system is set to start heating when the temperature in the building is lower than 20°C. Internal loads are assumed to be according to Table 4.5 which is more consistent with the life of a family not home with children than the house owners' present way of living.

Table 4.5 Internal loads in the building

Time	Moisture gain [g/h]	Heat gain [W/h]
0-6	25	200
6-8	400	300
8-16	25	200
16-22	200	400
22-24	25	200

4.3.2 Input data for the greenhouse

The greenhouse is modeled as a 4mm thick glass construction “flying” above a 20mm gap. The gap is a simplification of the untightness in the foundation. Table 4.6 gives the glass areas and Table 4.7 gives the properties for the glass. The ground is assumed to be 7 m of sand due to a lack of ground materials in the beginning, which is a deviation from the original ground.

Table 4.6 Areas of the greenhouse

	East/West gables	North wall	South wall	North/south roofs	Ground
A [m^2]	49	93.3	97.1	118.5	210

The difference in areas between the north and south wall is due to the subtraction of the area for the passage way. The greenhouse doors are sliding glass doors and they are assumed (and likely) to have the same properties as the greenhouse walls.

The inside volume for the empty greenhouse is 1045m3 and the roof angle is 27.6^o. The volume of the building is 248m^3 that is subtracted from the greenhouse volume when the building is modeled inside the greenhouse.

Table 4.7 Properties of the glass

		Diffuse	Direct					
d [mm]	α [°]		0	40	50	60	70	80
4	τ	0.78	0.86	0.85	0.83	0.78	0.67	0

The greenhouse can be ventilated by natural ventilation through the gap and through the hatches in the roof. In the reference greenhouse only the gap is used.

The effect of the hatches is modeled as an increase in the number of air changes in the greenhouse as the temperature rises see Table 4.8

Table 4.8 Air changes in the greenhouse due to temperature and degree of opening of the hatches

Temperature	-20	20	21	22	23	24	25
n [-/h]	0	0	1	2	6	8	10

The sand in the ground is modeled with properties as in table 4.9 below.

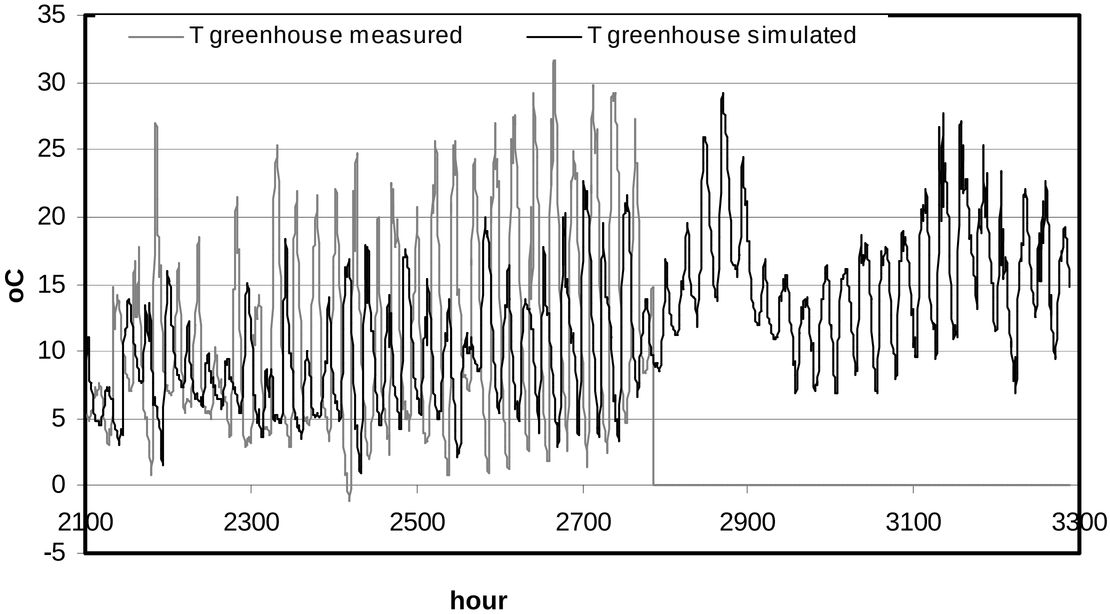
Table 4.9 Properties of the sand

Material	d [mm]	λ [W/m,K]	ρ [kg/m3]	c [J/kg,K]
sand	7000	0.64	1600	800

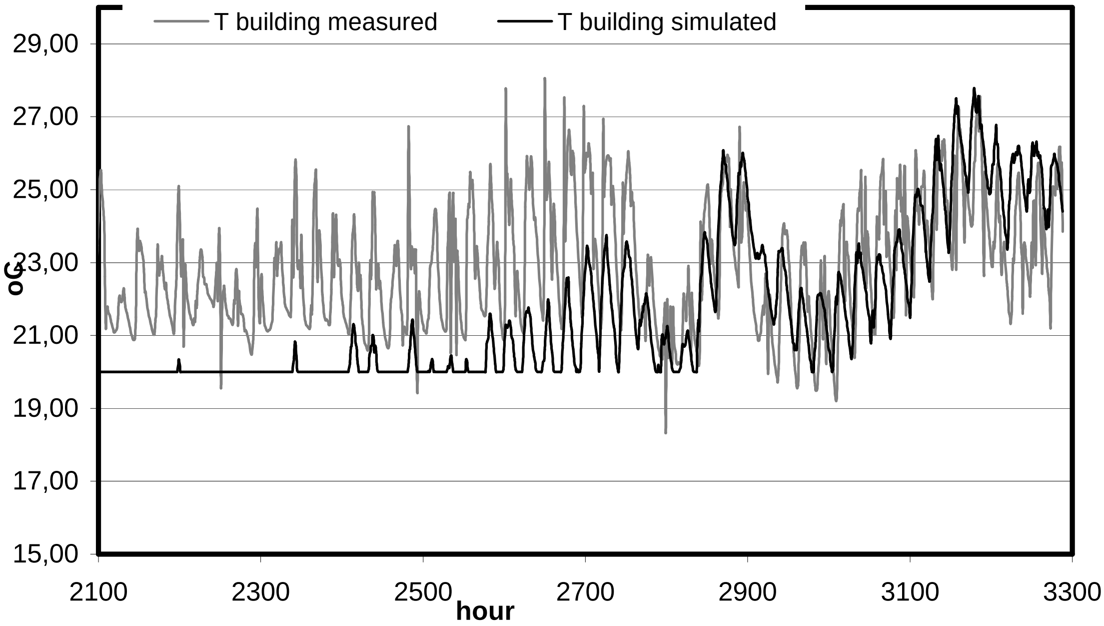
The capillary breaking function of the gravel in the real greenhouse is considered through modeling the sand without capillary suction.

4.4 Verification of the detailed model

The reasonability of the detailed model was controlled through running the simulations for a climate file based on the outdoor measurements made in Vare, see next chapter for description of the file, and comparing the simulated climate in the greenhouse and the building with the measured. Figure 4.2 shows the result for the final model.



a)



b)

Figure 4.2 Measured and simulated temperatures from March 28 to May 15 2008 a) in the greenhouse and greenhouse and b) in the building

As can be seen in both Figure 4.2 a) and b) the lines have the same period time and the temperature in the indoor climate follows the climate in the greenhouse. The deviation in temperature between the measured and simulated greenhouse climate, a), are reflected in the indoor temperature, b). Looking at a) the deviation between the measured and simulated greenhouse temperatures may have been caused either by improper placement of the measurement device or by false assumptions in the model. During the next period (where measured greenhouse temperature is missing) both the simulated and measured indoor temperatures, (see Figure 4.2b), follow each other rather well but now there is a problem in stating what the temperature in the greenhouse was like. However, since the trends for the curves are clear and reasonable and the reliability of the greenhouse measurements are discussable this is taken as the final model.

The LSA model has not been verified.

4.5 Climate data for the simulations

To verify the model the measured outdoor climate data from Vare, supplemented with data from Vistaberg, Huddinge was used. Since the measured data neither covers an entire year nor contains measurements of solar radiation a standardized climate file from SMHI (Swedish Meteorology and Hydrology Institute), covering Göteborg, was used for the simulations.

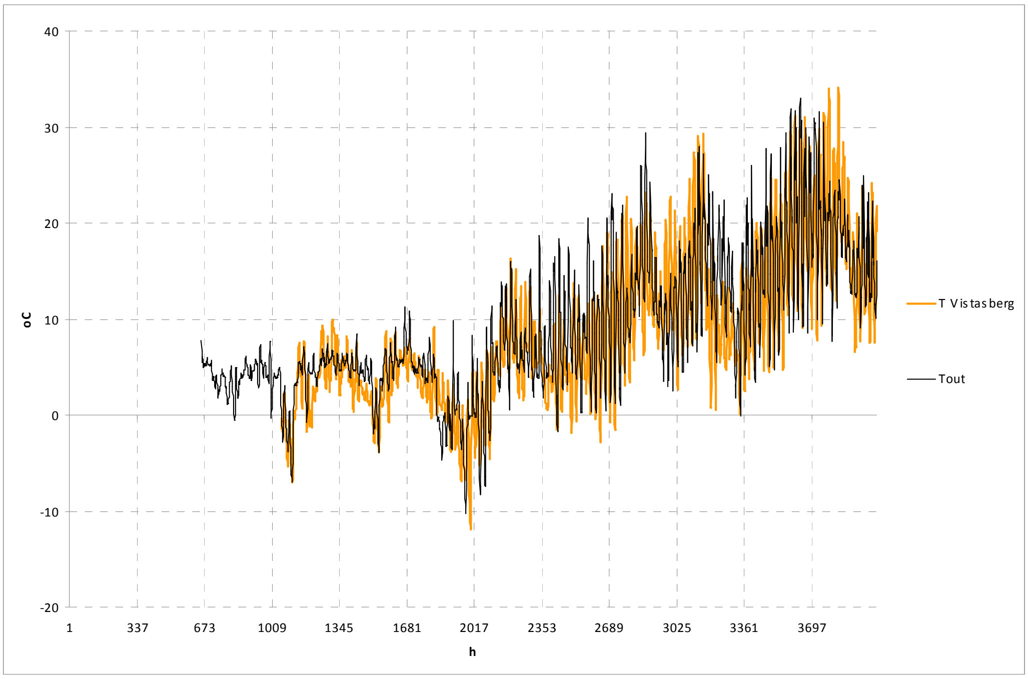
4.5.1 Climate files

Both the SMHI file and the file constructed from the measurements for this thesis are based on hourly mean values and constructed according to Table 4.10 below. The detailed model uses all the data while the LSA model only consider outdoor temperature and solar radiation (through the windows).

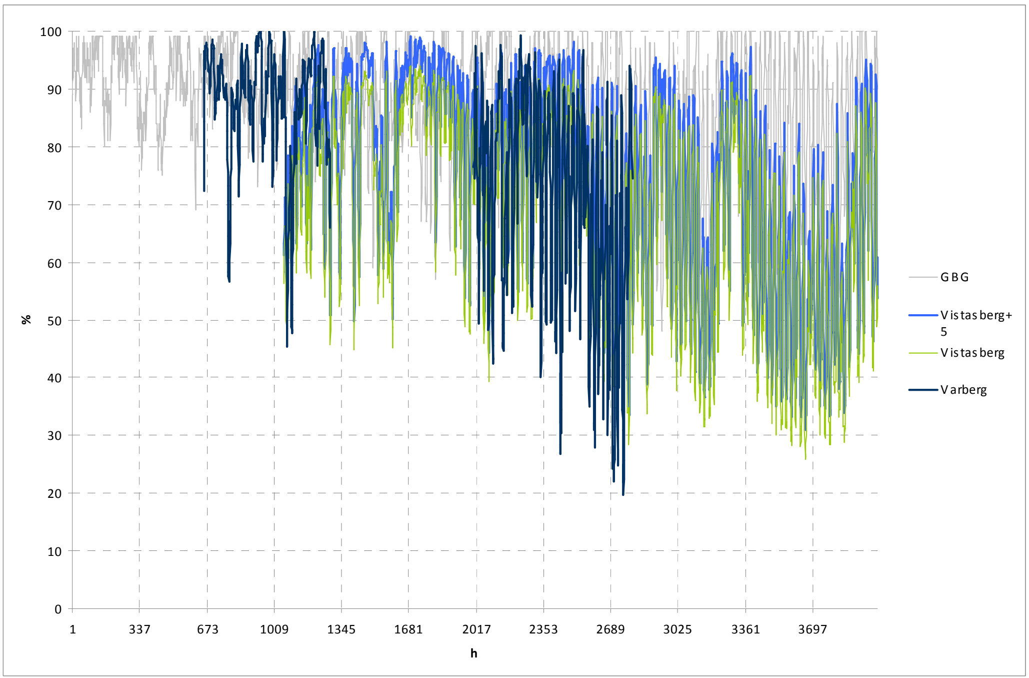
Table 4.10 Organization of the climate files

			Solar radiation				Wind	
Time [h]	T_{out} [°C]	RH [%]	Global (horizontal) [W]	Diffuse (horizontal) [W]	Beam (direct) [W]	LW [W]	Direction	Speed [m/s]

The verification file includes data from January 28 to June 16 2008 and is a combination of the measurements made at the site and measurements made by Chalmers for a project in Vistaberg during the same period. Both places are situated on the coast and despite the geographical distance the temperatures follow each other rather well during the period of interest, see Figure 4.3 a).



a)



b)

Figur 4.3 Comparison between the climates in Vare, Vistaberg and Göteborg. a) Temperatures. b) Relative humitidy.

Where no measurement result of the relative humidity in Vare is available 5 percentage units was added to the measurements from Vistaberg (blue line in figure 4.3 b)). Looking at the periods where there are measurements from Vare this seems to be an acceptable approximation.

The solar radiation data in the verification file is for Varberg taken from SMHI's webpage (SMHI, 2008).

5 Introduction and overview of simulations

Simulations were first used to assess the greenhouse's impact on the climate surrounding the building. Then the impact of making some changes in the greenhouse design was tested. As reference climate for these simulations a simulation of the original greenhouse without the ventilation system and sunscreens was used.

To evaluate the indoor climate and assess the building types two different types of simulations were made. The first were free running temperature simulations and the second were simulations with installations. Free running temperature simulations are simulating buildings without installations. It is a common way of evaluating how well the (planned) design itself is fitted to the surrounding climate. The simulations give an indication of the indoor climate when the building is only affected by the surrounding climate. Hence this type of simulation indicates what the HVAC systems will have to handle. Simulations with installations give a picture of the climate in the building when it is in use. The heading *Building with installations* includes heating system, ventilation and also internal moisture load. The effect of internal moisture and heat loads are discussed in Section 8.3.

The building was simulated alone and standing in the greenhouse in order to be able to compare its climatical behavior. Last different design types for the building (when placed in the greenhouse) were evaluated.

For the climate in the building the reference climate depended on what was examined. To assess the effect of placing the building in the greenhouse the original building standing without the greenhouse is used as reference. Comparisons of the effects of placing different building designs in the greenhouse were made with the original building placed in the greenhouse as reference. The temperature on the building's roof has not been simulated since this was not possible in the model.

Table 5.1 Overview of simulations

Chapter no	Simulation description
6	Simulated climate in the greenhouse (reference greenhouse climate)
7	Climate in the greenhouse depending on orientation, size, ventilation, sunscreens and adding a big thermal mass
8	Building without greenhouse- introduction to the building's behavior
9	Building in the greenhouse
10	Changing the building design. Original, light, heavy with equal U-values and a very heavy building and the original without roof insulation

6 Simulated climate in the greenhouse

The climate in the greenhouse (T_{gh}, v_{gh}) is affected by the outdoor conditions; temperature, vapor content (T_{out}, v_{out}) and the solar radiation together with the properties of the greenhouse where the transmittance of the glass (τ_{gh}), and the size of openings are the most important. The U-value of the glass is high and its heat storage capacity is low which makes the greenhouse dependent on the solar radiation to obtain and keep a different temperature than the one outdoors. The inflow of energy is then higher than the outflow.

6.1 Input for the greenhouse

The greenhouse is the same as described in Section 4.3.2. Only the gap is used as opening for the ventilation. The start temperature and relative humidity are set to 0°C and 80% respectively.

6.2 The simulated climate in the greenhouse

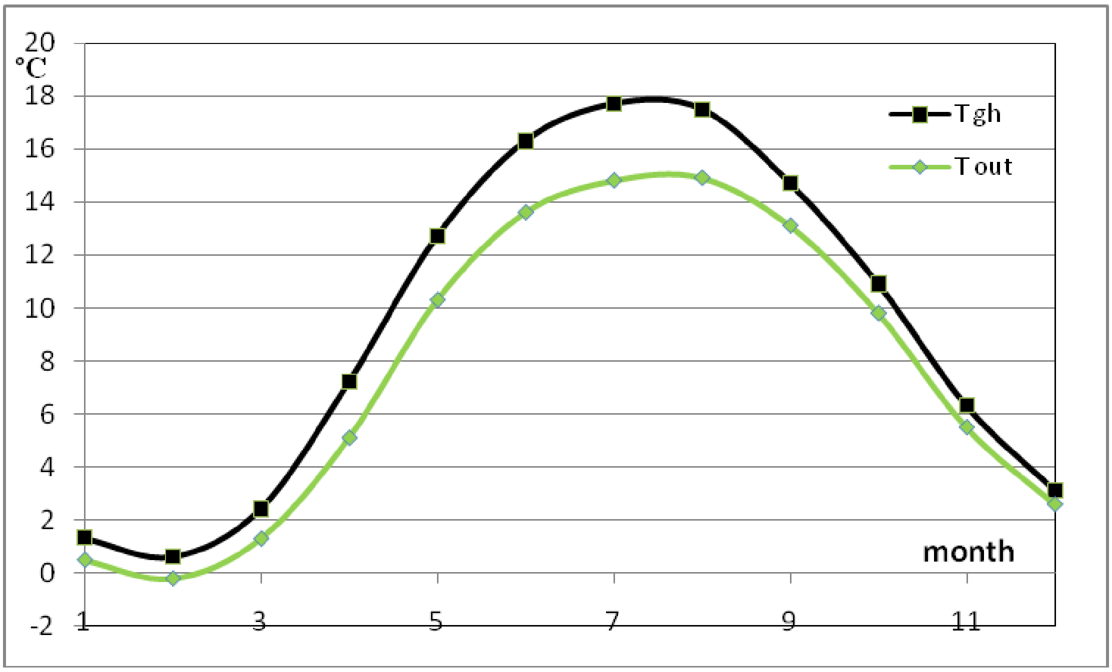
The simulated climate in the greenhouse compared to the Göteborg outdoor climate is presented below. Table 6.1 contains the monthly mean values that are plotted and discussed under the headings *temperature* and *relative humidity* respectively.

Table 6.1 Simulated monthly mean humidity and temperature

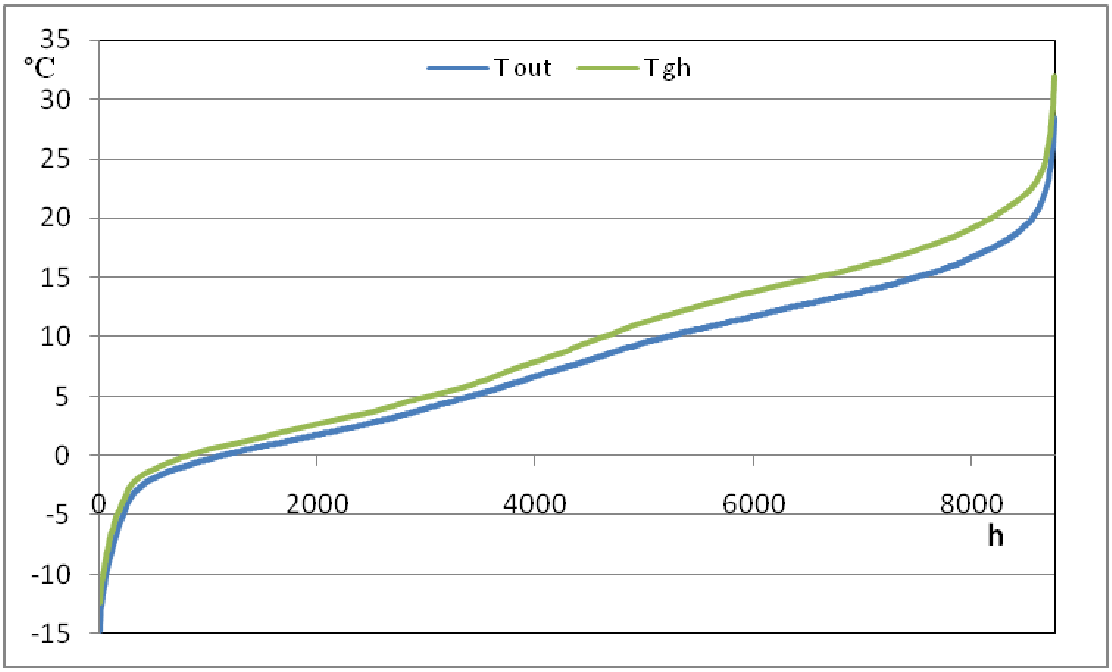
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T_{out} [°C]	0.5	-0.2	1.3	5.1	10.3	13.6	14.8	14.9	13.1	9.8	5.5	2.6
T_{gh} [°C]	1.3	0.6	2.4	7.2	12.7	16.3	17.7	17.5	14.7	10.9	6.3	3.1
RH_{out} [%]	92	90	87	82	83	82	83	84	85	88	90	90
RH_{gh} [%]	82	83	80	76	74	71	69	71	72	79	81	83

6.2.1 Temperature

Table 6.1 shows that the monthly mean temperatures are higher in the greenhouse than outdoors. In Figure 6.2 a) the values can be seen as curves and in b) are all the simulated values presented in a duration diagram.



a)



b)

Figure 6.2 a) Monthly mean temperatures in the greenhouse and outdoor b) duration diagram of the temperatures in the greenhouse and outdoors

The figures shows that the temperature difference between the greenhouse and outdoors increases with the outdoor temperature (e.g. with the solar radiation). The maximum difference in monthly mean is about 3 degrees and also the duration diagram shows that the difference in temperatures mainly is about a couple of degrees. The maximum simulated temperature in the greenhouse is 32°C for an outdoor temperature of 27.4°C. For the measured it was 45.5°C compared to 29°C. This is a rather big difference but it is hard to say what value is the most reliable. This is due to the measurement problems, the simplifications and assumptions made in the modeling and the use of different climates.

The number of hours with a temperature above 18°C inside the greenhouse is 1057 compared to 472 for the outdoor temperature. Those periods start in the middle of April and beginning of May for the greenhouse and outdoor respectively. Both end in the beginning of October. This trend is equal to the measured values and the greenhouse is warmer than the temperature outdoors in the spring but not during fall.

6.2.2 Relative humidity

The simulated relative humidity in the greenhouse is, as expected, lower than outdoors, Figure 6.3. Since the ground is assumed to have no capillary suction there is very little difference in vapor content between the greenhouse and outdoors, see Table 6.2. The difference in relative humidity is therefore almost only due to the temperature differences.

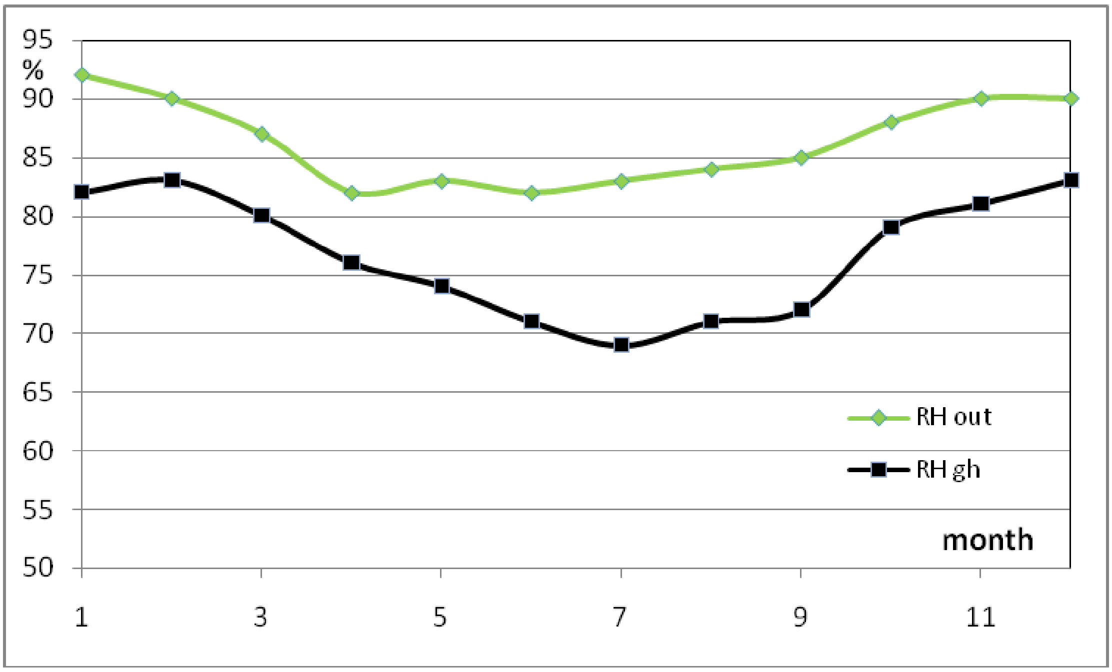


Figure 6.3 Simulated relative humidity in the greenhouse compared to the outdoor relative humidity.

Table 6.2 Monthly mean vapor content

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
v_{out} [g/m^3]	3.7	3.4	3.7	4.4	6.3	8.3	8.8	8.9	8.0	6.8	5.2	4.2
v_{gh} [g/m^3]	3.5	3.4	3.7	4.7	6.7	8.5	8.8	8.8	7.6	6.7	4.9	4.0
Difference [g/m^3]	-0.2	0	0	+0.3	+0.4	+0.2	0	-0.1	-0.4	-0.1	-0.3	-0.2

7 Parameters affecting the climate in the greenhouse

In this chapter the results from simulating different values of parameters that may have an impact on the climate in the greenhouse are presented. The parameters were orientation, size, ventilation rate, sun screening and adding a big thermal mass. The main focus is put on presenting the temperature since it is considered being the most interesting parameter for a greenhouse not used for cultivating. For most cases the impact the new temperature in the greenhouse had on the energy consumed for heating the building were evaluated. A warning should be raised for looking only at energy saving though, since warmer during winter probably also means warmer during summer and the summer temperatures are the most critical for comfort as will be seen in Chapter 8 and 9. Though there hopefully is a possibility to solve the summer temperatures through ventilating the indoor temperature down to equal the outdoor temperature.

7.1 Input and reference climate for the greenhouse and reference energy consumption for the building

Since this chapter is about the climate in the greenhouse the results from chapter 6 are used as reference climate. For the energy comparisons the result from Chapter 9 is used.

The changes in input for the cases that will be compared to the reference are described under each subchapter.

7.2 Impact of orientation

The impact of the orientation of the greenhouse was examined through rotating the greenhouse from its original position (long sides facing north/south) to let them face east/west and northeast/southwest. As can be seen in Table 7.1 below the temperature effects of the rotations were rather small.

Table 7.1 Monthly mean temperatures in the greenhouse for different orientations of the long sides.

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
N/S (ref)	1.3	0.6	2.4	7.2	12.7	16.3	17.7	17.5	14.7	10.9	6.3	3.1
NE/SW	1.3	0.6	2.4	7.2	12.8	16.3	17.7	17.5	14.7	10.9	6.3	3.1
E/W	1.3	0.8	2.6	7.7	13.4	16.5	17.9	17.7	14.8	11.3	6.3	3.1

The 45° rotation made almost no difference at all while the 90° turn raised the temperature with maximum 0.7 degrees. Since the 0.7°C raise occurs in May and the second largest difference (0.4°C) occurs in October there is reason to conclude that orientation has the largest impact during spring and autumn. This seems reasonable since the intensity of solar radiation is then rather high in comparison to the air temperature and collecting the direct beams during the sunny hours can make a difference. The overall small effect of the orientation is most likely due to the high transmission losses for the greenhouse.

7.2.1 Energy consumption

Even if the temperature differences in the greenhouse are small there is a possibility to save heating energy through using the orientation. As can be seen in Table 7.2 turning the buildings into an east/west orientation saves, at least in theory, almost 9%.

Table 7.2 Energy consumed for heating due to the orientation of the long sides of the greenhouse and the building

	N/S (ref)	NE/SW	E/W
kWh/m2,year (kWh/year)	88.5 (5576)	82.0 (5165)	80.7 (5086)
Difference		-7.3%	-8.8%

The main reason for the energy savings is probably that the building was rotated together with the greenhouse that made the direction of the glass parts (especially the eastern glass façade) change see Figure 7.1.

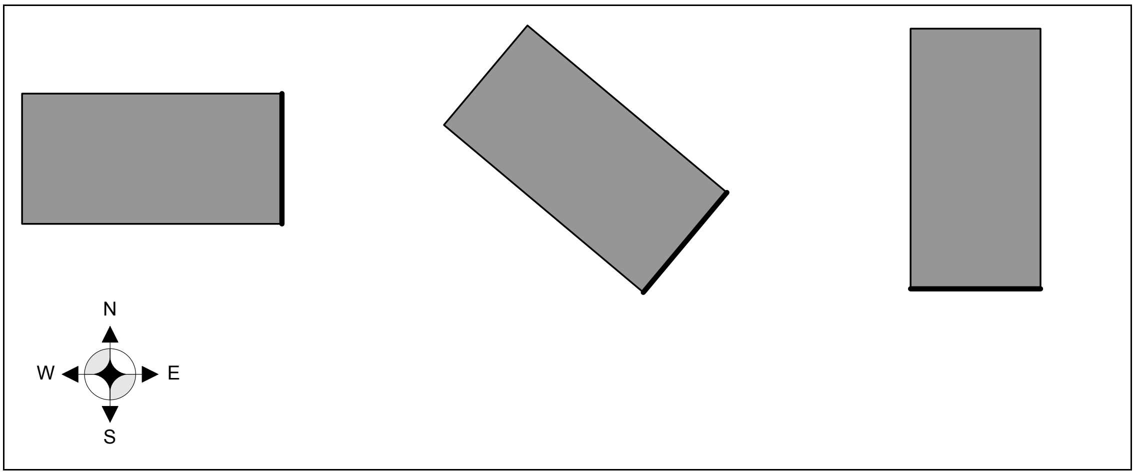


Figure 7.1 Orientation of the glass façade in the building

Figure 7.2 shows the temperature in the building in May; note that the rotated buildings have almost the same temperature compared to the greenhouses where the temperature for the original and 45° rotation was similar.

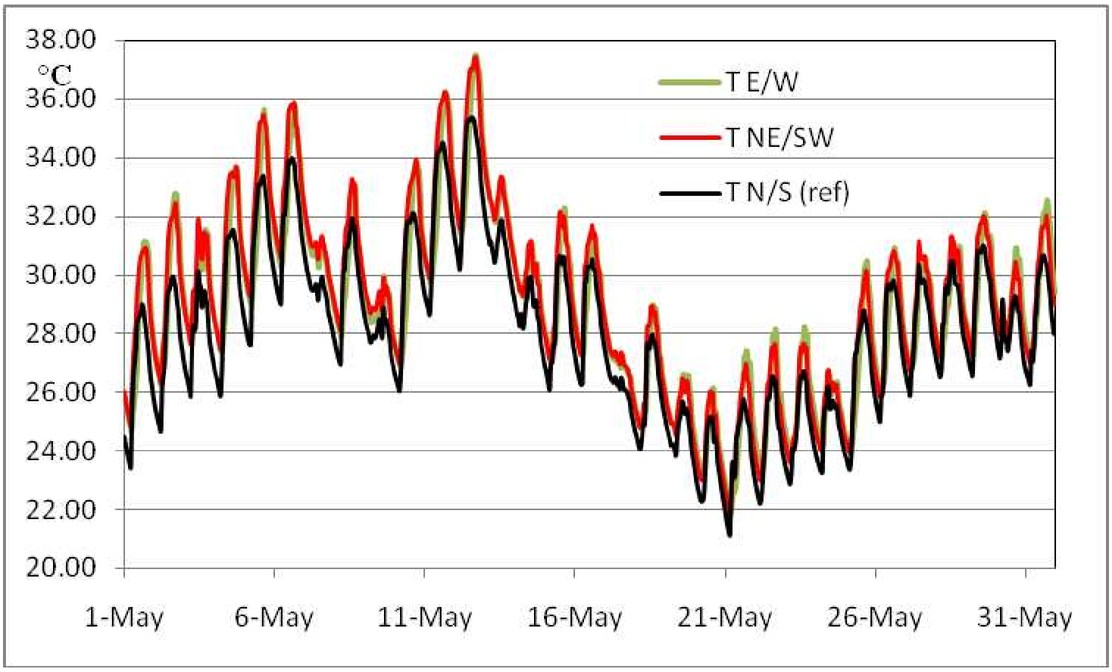


Figure 7.2 Temperatures in the building (with surrounding greenhouse) for different orientations

The rotation caused an increase in the indoor temperature of 1.1°C for the NE/SE case and 0.9°C for the E/W rotation compared to the increases of the greenhouse temperature that were 0.7 and 0.1 respectively.

7.3 Impact of the size of the greenhouse

The analysis of how the temperature in the greenhouse is dependent on the size was made through comparing one smaller and three larger greenhouses to the original size. The small greenhouse had the same width as the original but only half of the length and 1m lower ridge height. For the larger greenhouses the first had the same height as the original but the lengths of the sides were doubled. For the second also the height was doubled. The third greenhouse was a square building of 500×500 m and 30m high. The roofs were in all cases a saddle roof sloping towards the north and south (as in the original greenhouse), but since the dimensions differed so did the angle of the roof. The dimensions for the greenhouses can be seen in Table 7.3. All greenhouses were ventilated through a 20mm gap along the ground, as in the reference case.

Table 7.3 Dimensions for the greenhouses

	Long side [m]	Short side [m]	Ridge height [m]	Roof angle [°]	Volume [m^3]
Original	25	8.4	6	27.6	1047
Small	12.5	8.4	5	14.7	510
Double, low	50	16.8	6	14.7	4187
Double, high	50	16.8	12	27.6	8373
Large	500	500	30	3.4	5625000

The resulting monthly mean temperatures for the different sizes are listed in Table 7.4 and plotted in Figure 7.3.

Table 7.4 Monthly mean temperatures for the different sizes of the greenhouse

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Ref	1.3	0.6	2.4	7.2	12.7	16.3	17.7	17.5	14.7	10.9	6.3	3.1
Small	1.2	0.6	2.3	7.0	12.5	16.0	17.3	17.2	14.5	10.8	6.2	3.1
Double low	1.7	1.1	3.0	8.3	14.0	17.9	19.4	18.9	15.7	11.5	6.7	3.4
Double high	1.6	0.9	2.8	7.8	13.5	17.2	18.7	18.2	15.3	11.3	6.5	3.3
Large	3.0	2.3	5.3	12.8	20.0	24.1	25.9	23.5	18.8	13.4	7.6	4.0

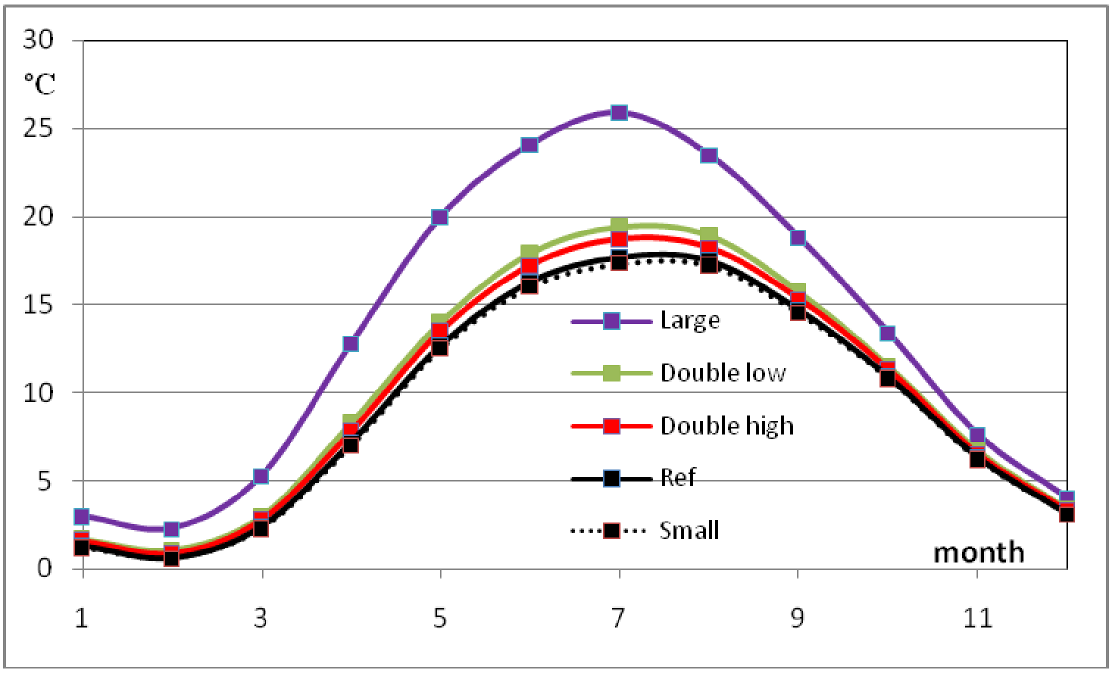
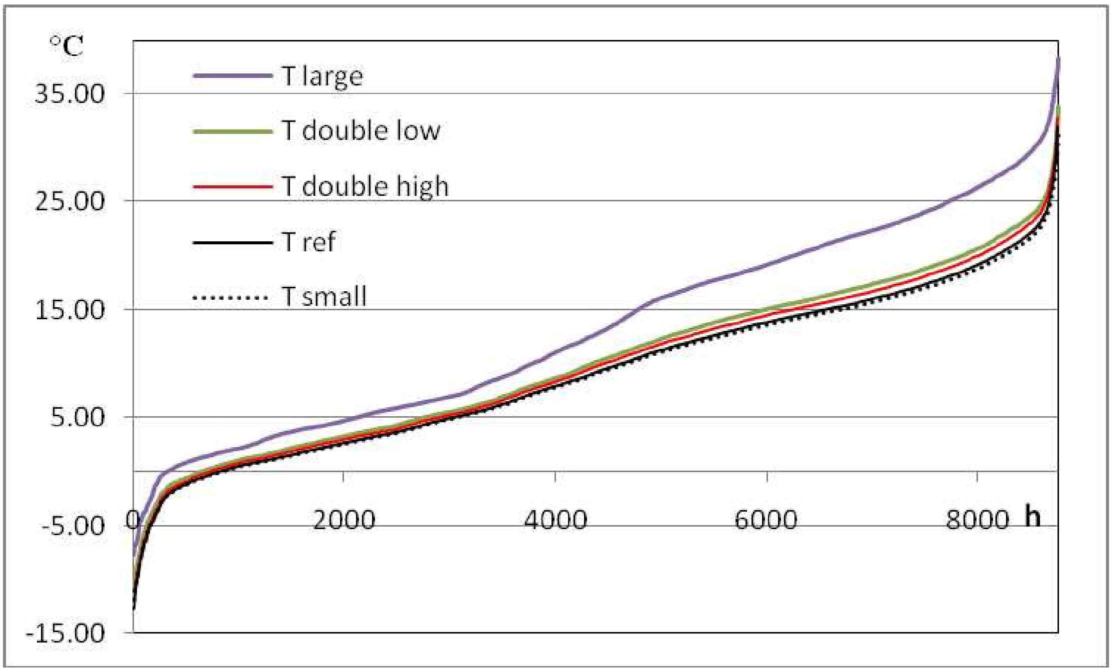


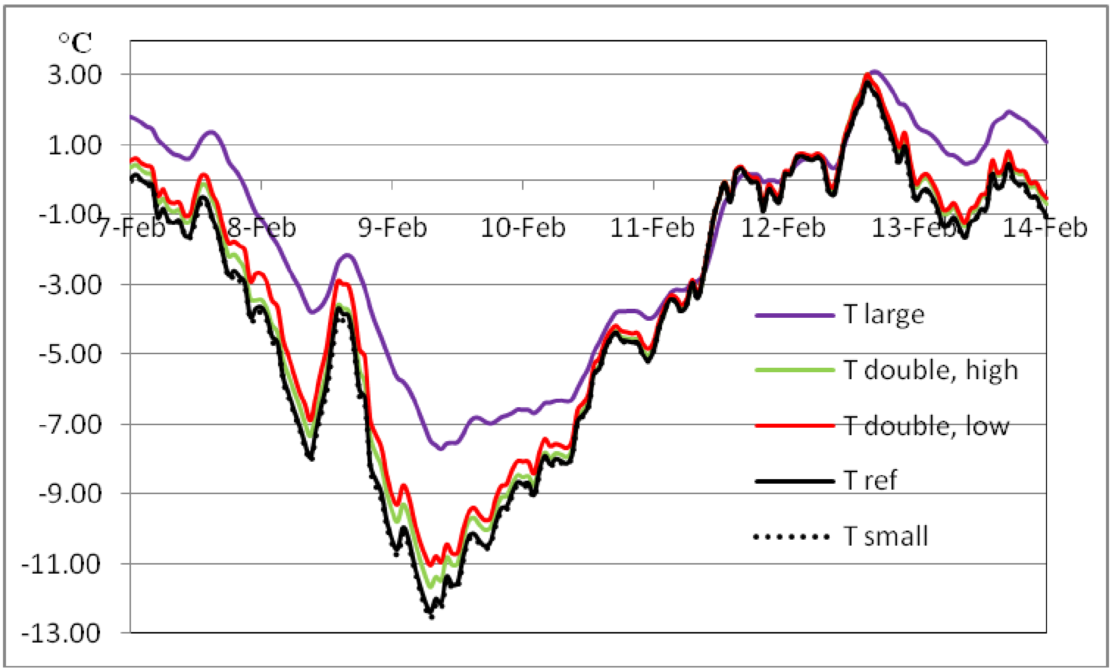
Figure 7.3 Monthly mean temperatures for the different sizes of the greenhouse.

The monthly mean temperatures show that the temperature in the greenhouse increases with the size and that the differences are most distinct during the summer. Though for the cases where only the ridge height (i.e. the volume) differs is the greenhouse with the smaller volume the warmest.

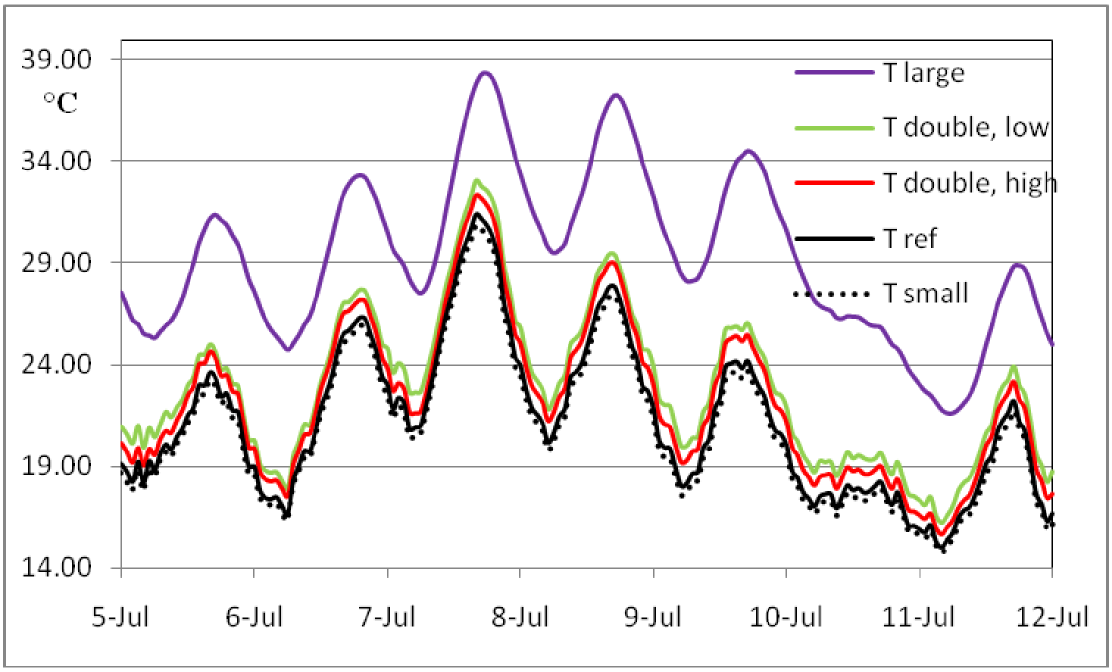
To give a more detailed picture of how the temperatures differs between the greenhouses a duration diagram and the temperatures during the weeks containing the coldest and the warmest outdoor temperature are shown in Figure 7.4.


°C
35.00
25.00
15.00
5.00
-5.00
-15.00
0
2000
4000
6000
8000
h
T large
T double low
T double high
T ref
T small

a)


°C
3.00
1.00
-1.00
-3.00
-5.00
-7.00
-9.00
-11.00
-13.00
7-Feb
8-Feb
9-Feb
10-Feb
11-Feb
12-Feb
13-Feb
14-Feb
T large
T double, high
T double, low
T ref
T small

b)



c)

Figure 7.4 Temperatures for different greenhouse sizes. a) Duration diagram over a year. b) Temperatures during 6-12 February. c) Temperatures during 7-13 July.

The duration diagram shows that all the curves follow the same shape. Noticeable is that for neither of the greenhouses the maximum temperature exceeds 40°C, which still makes them colder than warm days close to the Mediterranean. As can be seen in b) and c) the large greenhouse is the warmest both during the warm and the cold week, even if the magnitude of the difference differs from about 5°C during summer to, more varying, about 1°C during winter. The curve for the large greenhouse is also smoother than the ones for the smaller greenhouses. The deviation from the outdoor temperature increases for all the greenhouses during summer.

Like other buildings greenhouses get heated by the energy in solar radiation and cooled by transmission losses. Since glass transmits most of the solar energy and has a high U-value greenhouses are easily affected by both solar radiation and the temperature difference to the surrounding climate. The smaller greenhouses encloses smaller air volumes and are therefore quicker heated (see the deviation between the peaks in b) and c)) but they also have a larger percentage of surface area and are therefore more affected by the surrounding climate than the large greenhouse. Since the heat capacity of air is low the transmission probably only a minor part in the explanation of why the large greenhouse is that much warmer. The ventilation is another factor, the gap percentage (gap area/enclosed air volume) is also lower for the large greenhouse and the ventilation is poorer, even though stack effect increases with increased temperature differences this is probably not enough to compensate. The warmer temperature during winter and the smoothness of the curve are probably effects of the heat capacity of the ground. The warmer summer temperatures, the larger “floor” area and the fact that the heat capacity of the ground is much higher than the one for air allows the large greenhouse ground to save a lot of energy that then heats the air during winter.

Another detail that may be of importance is the roof angle. The roof angle declines with the size of the simulated greenhouses and since the transmittance of the glass is higher (for direct light) the more straight the beams hit the surface (see Table 4.7) a flatter roof will allow more energy into the greenhouse. For the case with the same roof angle it is the building with the smallest volume that gets the highest temperature. This seems reasonable with the explanation above since the same amount of solar energy then is used to heat two different air volumes.

To fit the futuristic vision of a city created underneath a dome and to see the effect of a spherical roof it was desirable to model a dome unfortunately this was too complex modeling to fit into this thesis.

7.3.1 Energy consumption

For the energy needed for heating the doubling has a slight energy saving effect while the large greenhouse saves about 12 kWh/m^2, year, see Table 7.5.

Table 7.5 Energy consumed for heating the building for different sizes of the greenhouse

	Original	Small	Double, low	Double, high	Large
kWh/m^2, year (kWh/year)	88.5 (5576)	87.5 (5511)	84.2 (5307)	85.3 (5374)	76.3 (4810)
Difference [%]		-1	-5	-4	-14

The result for the smaller greenhouse is uncertain since the smaller the greenhouse the larger the impact of the building is most likely and this is not considered in the model.

The energy savings are less than for rotating the greenhouse for all greenhouses except the largest.

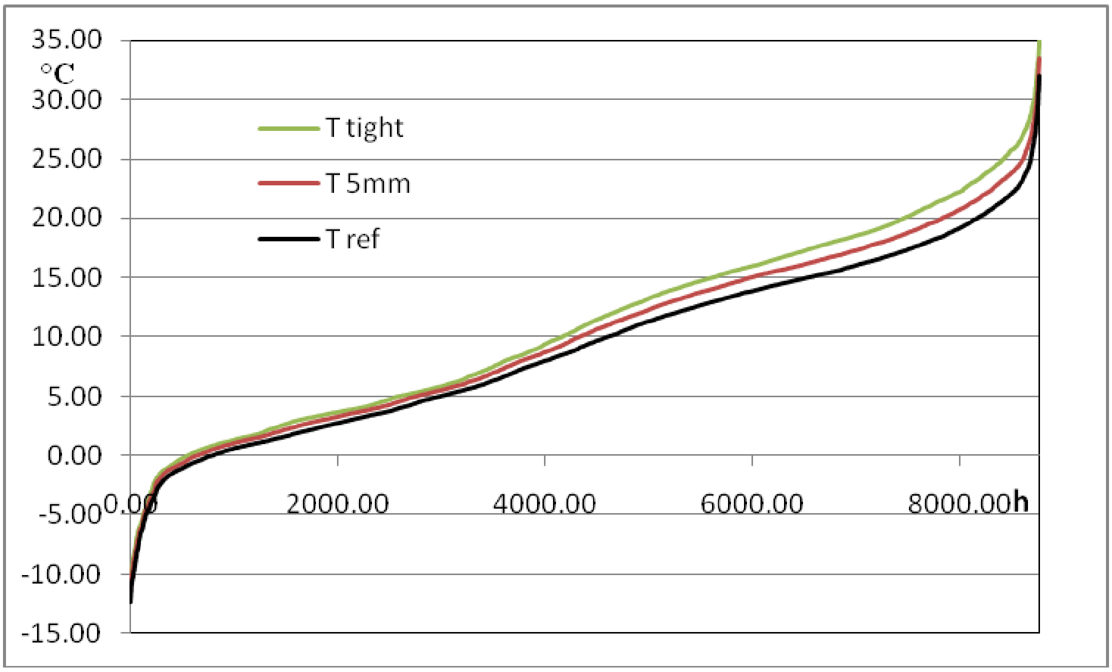
7.4 Impact of ventilation

The impact of the ventilation is divided into two parts. In the first the tightness of the greenhouse itself was increased and in the second a simplified version of the climate controlled hatches was used. The greenhouse in both cases was ventilated through natural ventilation.

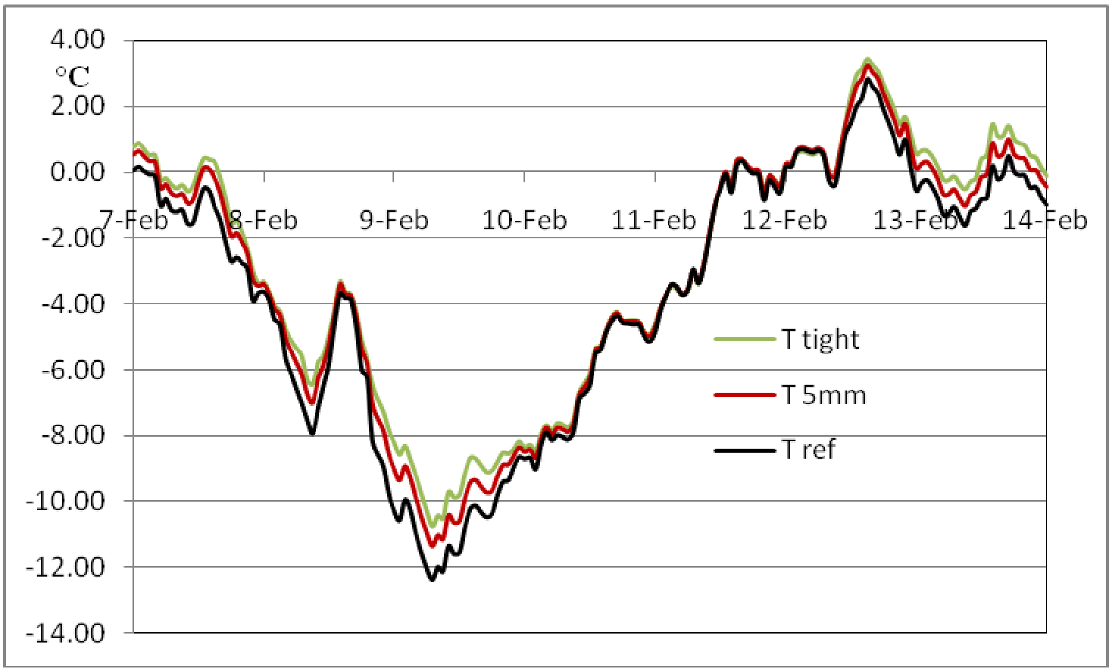
7.4.1 Increasing of the greenhouse air tightness

The model is constructed with the greenhouse itself initially tight except for a gap between the base and the glass in the walls. The gap is a simplification of the leakages in the base. In the reference greenhouse a gap of 20mm was used and when the tightness of the greenhouse was increased the gap was first reduced to 5mm and then completely closed.

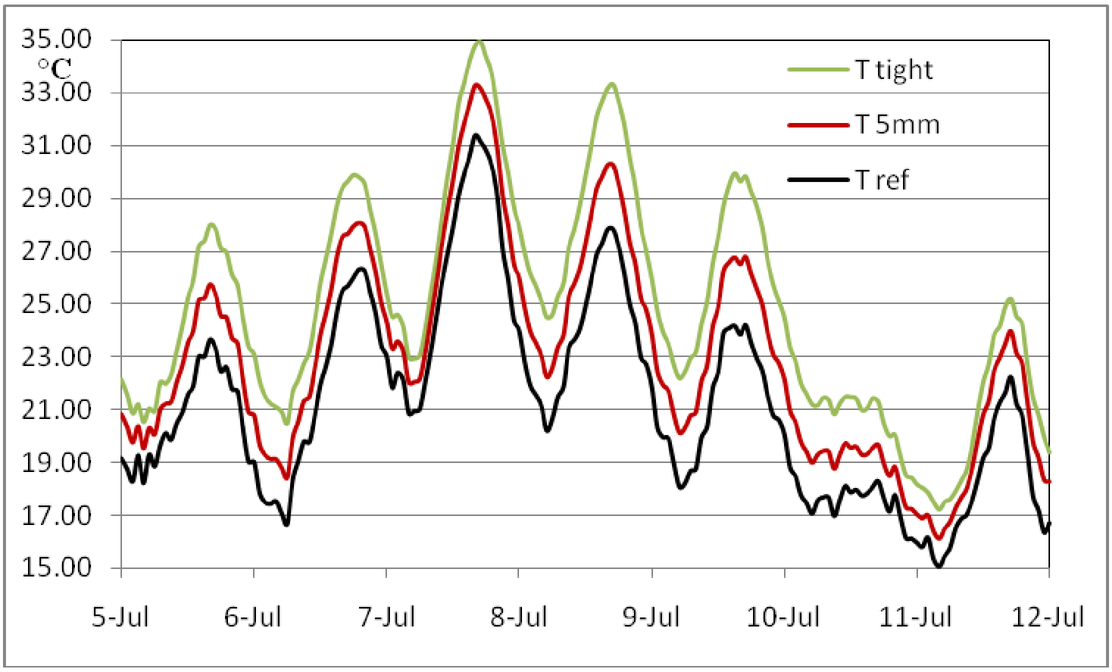
The results on the temperature in the greenhouse during a year can be seen in Figure 7.5 below. First in a duration diagram and then for the weeks containing the coldest and warmest outdoor temperature respectively.


35.00
°C
30.00
25.00
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
0.00
2000.00
4000.00
6000.00
8000.00
h
T tight
T 5mm
T ref

a)


4.00
°C
2.00
0.00
-2.00
-4.00
-6.00
-8.00
-10.00
-12.00
-14.00
7-Feb
8-Feb
9-Feb
10-Feb
11-Feb
12-Feb
13-Feb
14-Feb
T tight
T 5mm
T ref

b)



c)

Figure 7.5 Temperatures in the greenhouse for different tightness. a) Duration diagram. b) 7-14 February. c) 5-12July.

All the Figures above show that the temperature increases with the tightness and b) and c) that this difference increases when the temperatures rise. The mean temperatures for the cold and the warm week are presented in Table 7.6, showing a difference of 0.7 °C for the cold week and 3.6 °C for the warm week when comparing the original to the tight; the differences for the middle tightness are 0.5°C and 1.8°C respectively.

Table 7.6 Mean temperatures for the weeks containing the extreme temperatures

	Cold week [°C]	Warm week [°C]
Reference greenhouse	-3.7	21.3
5 mm gap	-3.2	23.1
Tight	-3.0	24.9

That the temperature is higher in the tighter greenhouse is reasonable since the openings for bringing colder air in then is smaller. The reason for the increased differences when the weather gets warmer is that even if the warmer temperature increases the stack pressure in the greenhouse this is not enough to compensate for the smaller gap, its low position and the fact that the amount of cold air that can be heated is small which causes the air to almost stand still. The increased temperature in the greenhouse reduces the need for heating of the building somewhat, see Table 7.7.

Table 7.7 Energy consumed for heating of the building for different tightness of the greenhouse.

	Ref	5mm	Tight
kWh/m^2,year (kWh/year)	88.6 (5576)	84.0 (5290)	82.3 (5186)
Difference [%]		-5	-7

Creating a completely tight greenhouse is not realistic and even the 5mm gap would be very hard to obtain (there is also a risk that the air quality in the greenhouse would be rather bad) but it is interesting to see the theoretical effects none the less.

7.4.2 Impact of opening the hatches

Opening the hatches allows air to flow through the greenhouse. Cold air is flowing in through the gap, rises as it gets heated and leaves the greenhouse through the hatches. Since this process speeds up with increased temperature difference between the inflowing and out flowing air the operation of the hatches, as mentioned in Chapter 2.2.1, is assumed to be governed by the temperature in the greenhouse.

The effect of opening the hatches was simulated through regulating the degree of opening of the hatches from 0-100%. The steps 0, 50, 75 and 100% were tested (0% corresponds to closed hatches which is the reference case). The number of air changes per hour in the greenhouse due to greenhouse temperature and degree of opening can be seen in Figure 7.5. The hatches are only in use when the temperature in the greenhouse is above 20° C.

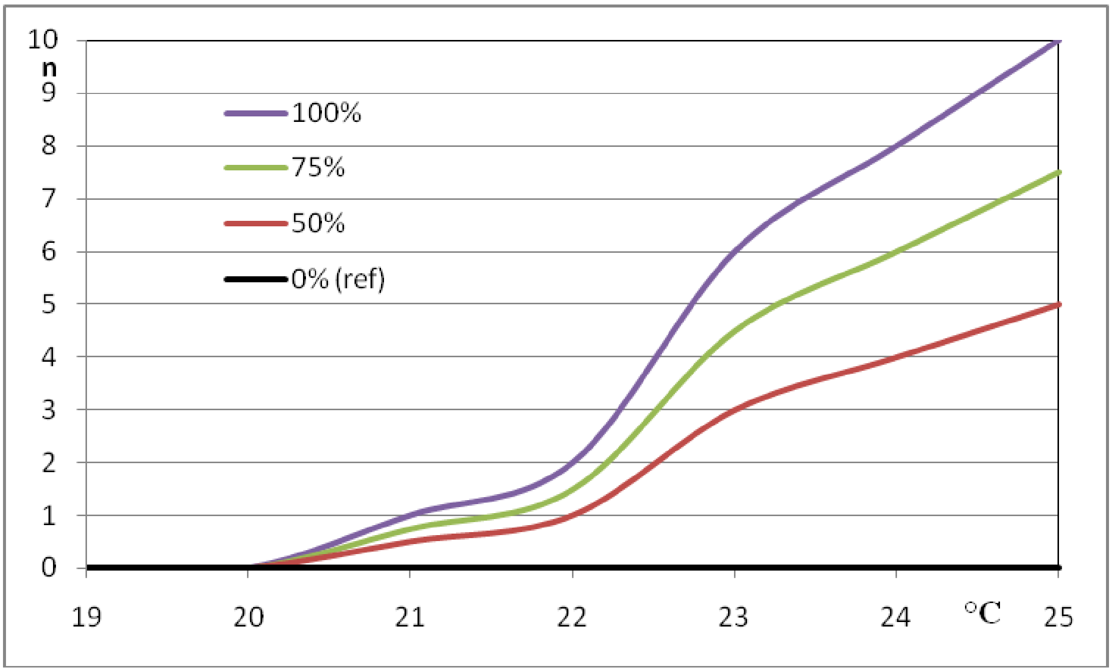
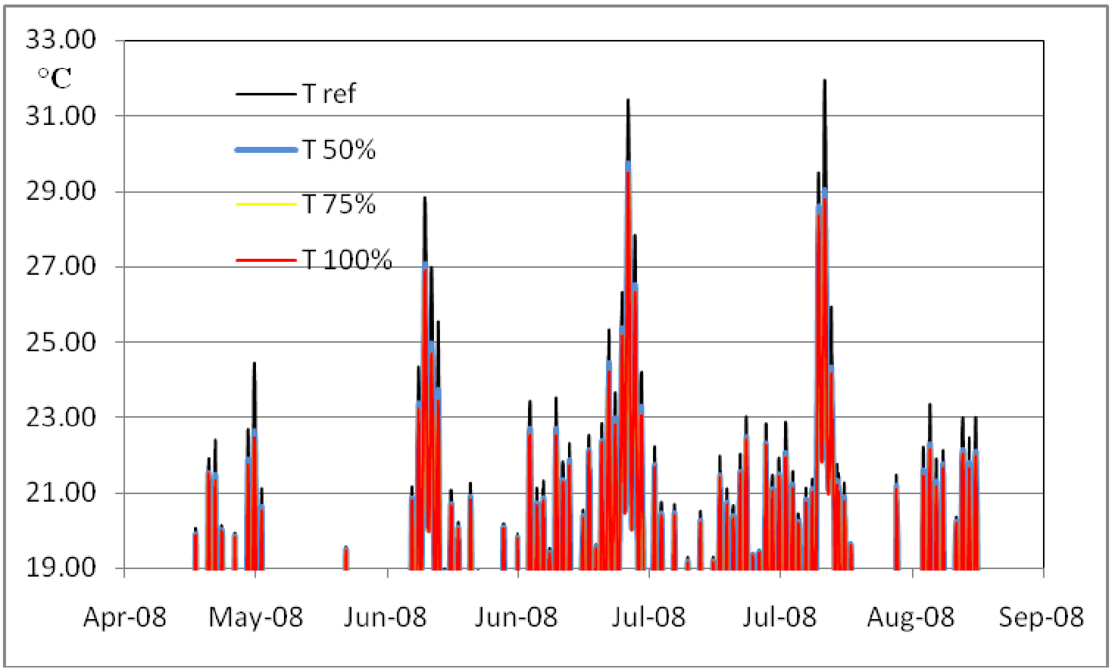
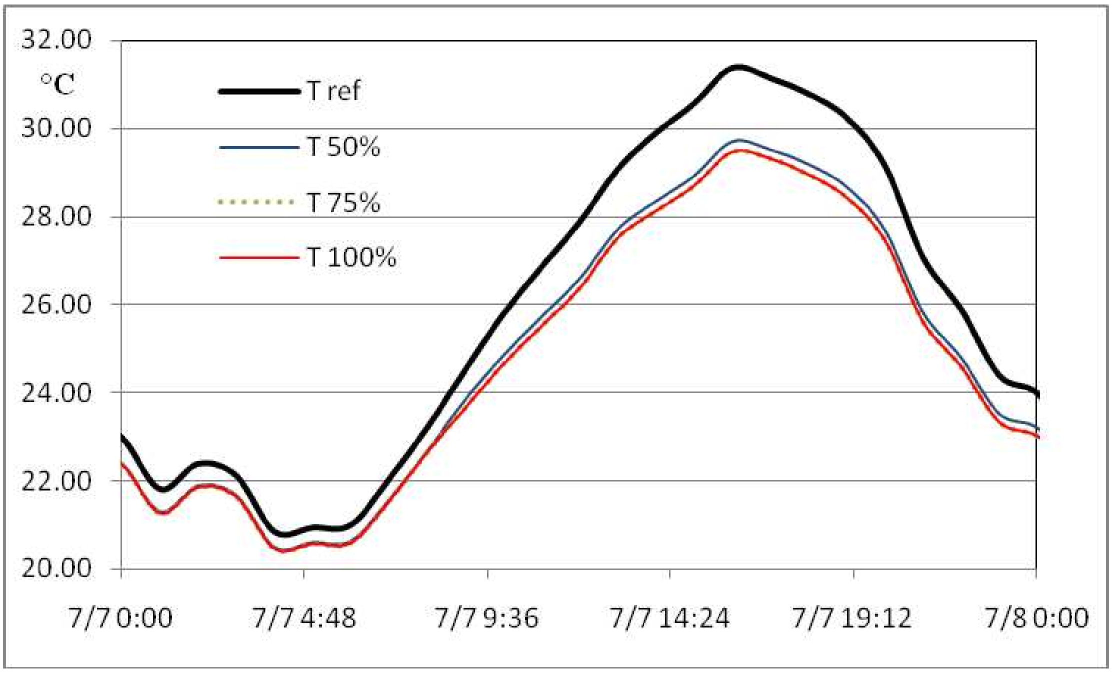


Figure 7.5 Air changes in the greenhouse due to temperature and degree of opening of the hatches

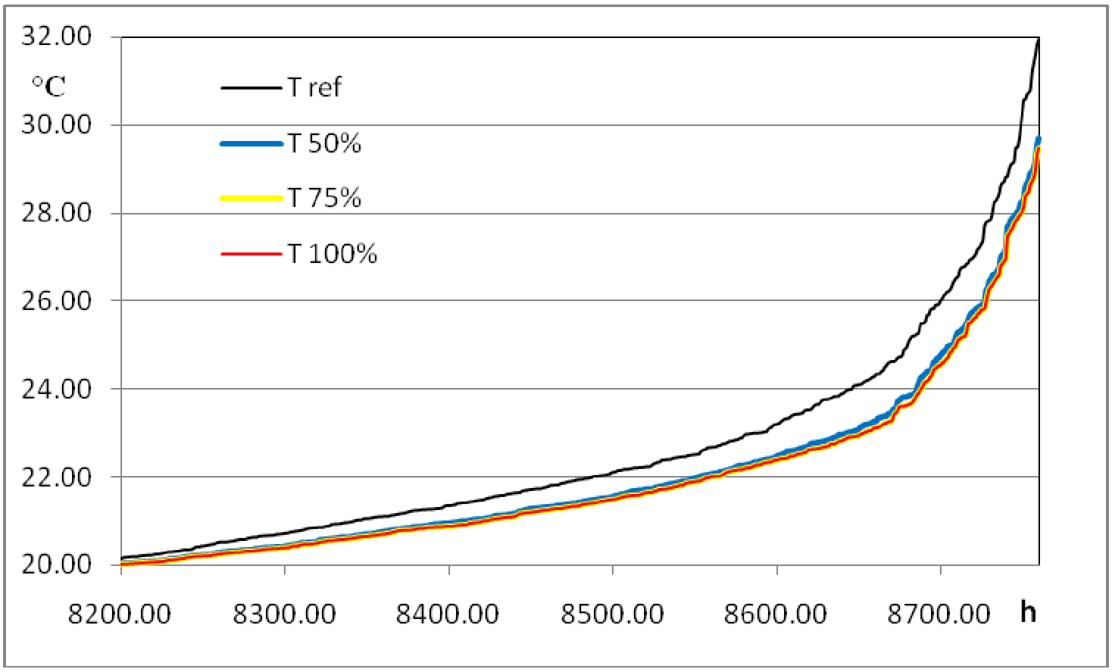
The hatches' task is to prevent the temperature in the greenhouse from rising too high. The temperature dependency, both for the use of the hatches and for the air change rate, makes their impact higher the higher the temperature, see Figure 7.6. The degree of opening appears to be of less importance.



a)



b)



c)

Figure 7.6 Temperatures in the greenhouse for different degree of opening of the hatches. a) Heat peaks. b) Temperatures during the warmest week. c) Duration diagram.

7.5 Impact of sun screening

The temperature impact of sun screening was modeled through adding screens that covered 0, 50, 75 and 100% of the roof area, where 0% represents the reference case. The screens transmitted 83% of the direct light and 75% of the diffuse light. The simulations were run with the same coverage for a whole year. A duration diagram over the differences in temperature inside the greenhouse is presented in Figure 7.8.

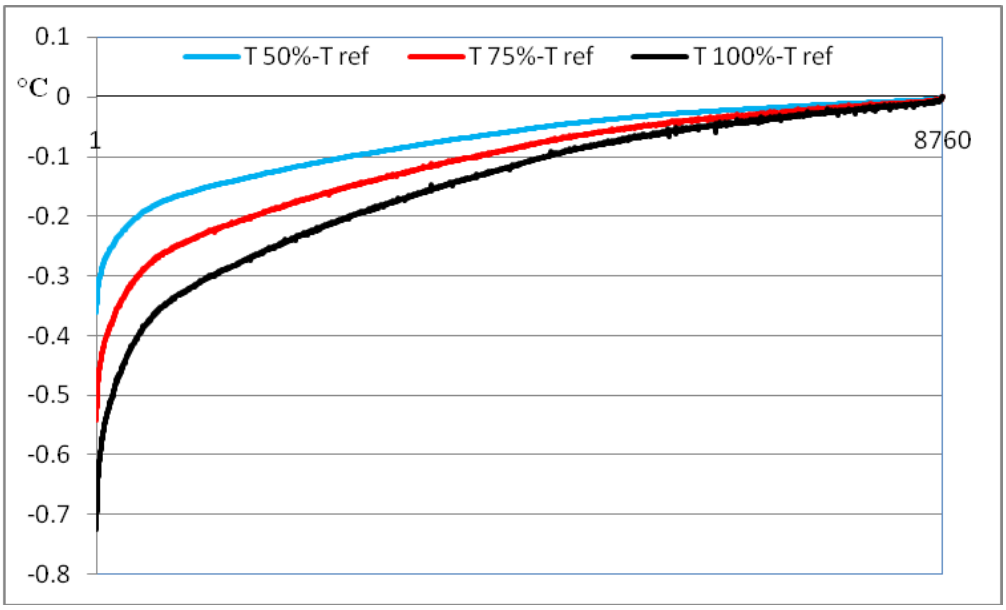


Figure 7.8 Difference in temperature between the reference case and the cases with screened roof

The Figure shows that the differences in temperature increase with the coverage grade. It also shows that the maximum difference is only 0.72°C. This is a small value but it is in accordance with the measured results where no difference could be noted in the measured air temperature after the installation of the screens. For a clearer figure of the difference between the different grades of coverage are the results for the warm week shown in Figure 7.9.

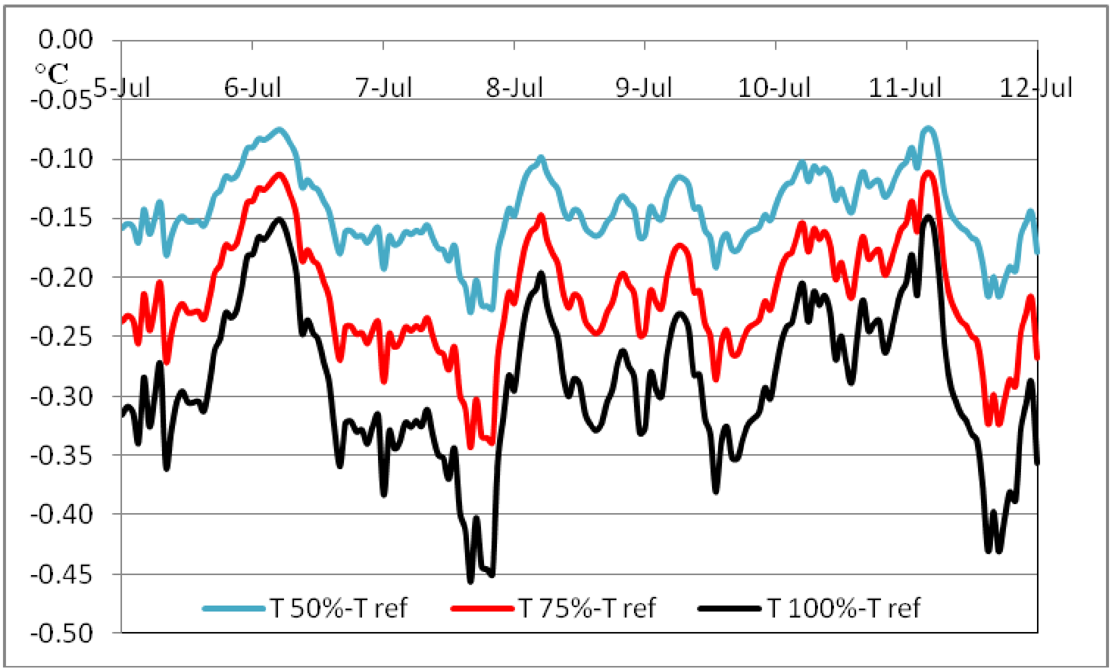


Figure 7.9 Difference in temperature between the reference case and the cases with screened roof during 7-13 July

Since the screens are placed inside the greenhouse they can only shade the interior. This excludes protection of the greenhouse itself from the solar radiation and allows both the glass to be heated and the solar energy to be transmitted into the greenhouse.

7.6 Adding a big thermal mass to the greenhouse

In chapter 8.3 the heat buffering capacity of the ground was part of the explanation of the warmer temperature in the large greenhouse. In order to see if adding a big artificial thermal mass to the original greenhouse would raise the winter temperature in the greenhouse the northern glass façade was replaced by a 10 cm thick concrete wall. The reason for choosing to replace the material in the façade, even though it affects the inlet of light, and not adding the mass inside the greenhouse (i.e. using the building) was that the greenhouse model does not sense what is inside it. The northern wall was selected because it is assumed to have the least impact on the climate in the greenhouse concerning inlet of solar radiation. The desired result was that the temperature during winter should get slightly warmer and the temperature during summer slightly colder. Taking a looking at the differences in temperatures though (T_{ref}-$T_{concrete}$), Table 7.8, shows that the temperature increases during the winter but even more during the summer.

Table 7.8 Increase in monthly mean temperature caused by the concrete wall

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Increase [°]	0.1	0.1	0.2	0.3	0.4	0.4	0.4	0.4	0.2	0.1	0.1	0.1

The explanation lies in the thickness of the wall. In chapter 12 is the heat buffering effect of materials described. As the wall tries to be in balance with the surrounding temperature its surface absorbs heat during the warm day and releases it during the colder night. The absorbed heat penetrates deeper and deeper into the material as long as there is a positive temperature difference e.g. the affected material is warmer than the unaffected. When the surface instead gets cooled by the surrounding air the energy gradually starts to flow out of the material starting from the surface. Those processes are always working. For thick materials though the warm or cold periods are not always enough to counteract all the effect from the previous, a shorter or less intense colder period can leave some heat in the material that continues to try to distribute itself evenly to the surrounding material just as one warm spring day may not be enough to thaw the entire snowman. The concrete wall is only thick enough to store heat for about 2 days, meaning that if the that if the surrounding temperature was constant the wall would have an evenly distributed temperature all through the material after 2 days and this is why the wall only has a short term effect, while the ground being several meters thick can store energy from summer to winter. The effect this has on the energy use in the building is less than 0.5% saving. The energy use drops from 86.6kWh/m^2, year to 86kWh/m^2, year.

8 The building without greenhouse- introduction to the building's behavior

Figure 8.1 shows a simple description of the model of the building.

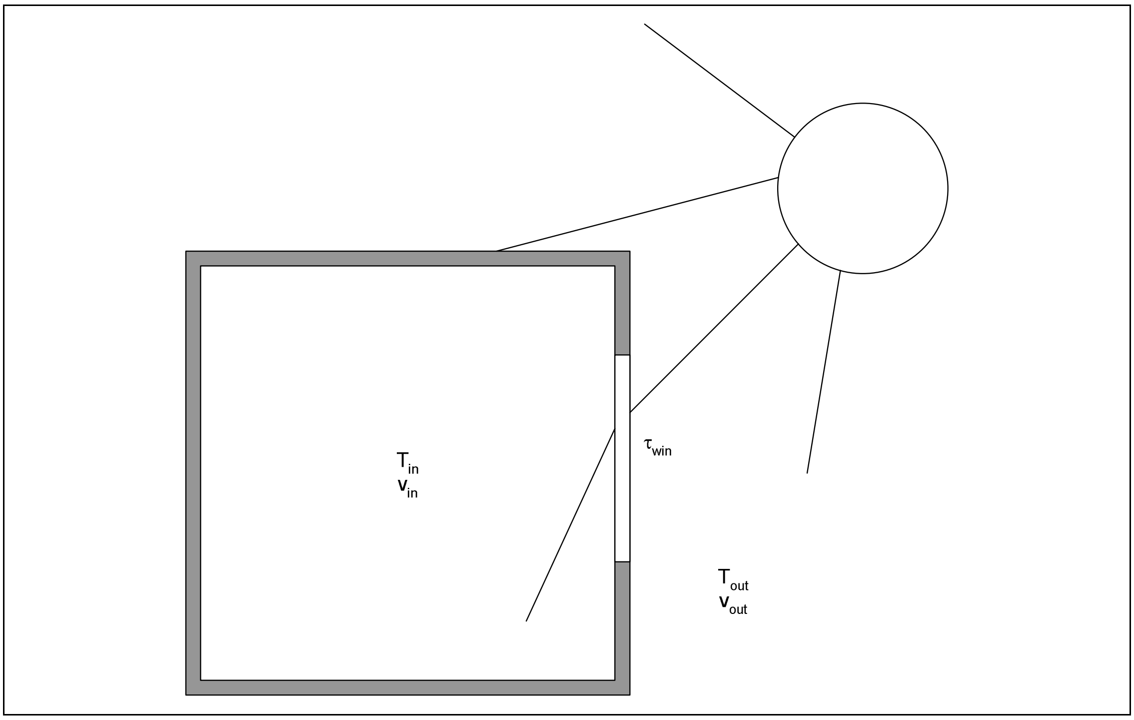


Figure 8.1 Schematic picture of the climate in the building. The indoor climate is affected by outdoor conditions and the buildings properties.

The indoor climate (T_{in}, v_{in}) is affected by the outdoor conditions; temperature, vapor content (T_{out}, v_{out}) and the solar radiation together with the properties for the building materials; conductivity, transmittance (τ_{win}), heat storage capacity and absorbance.

8.1 Basic input for simulations

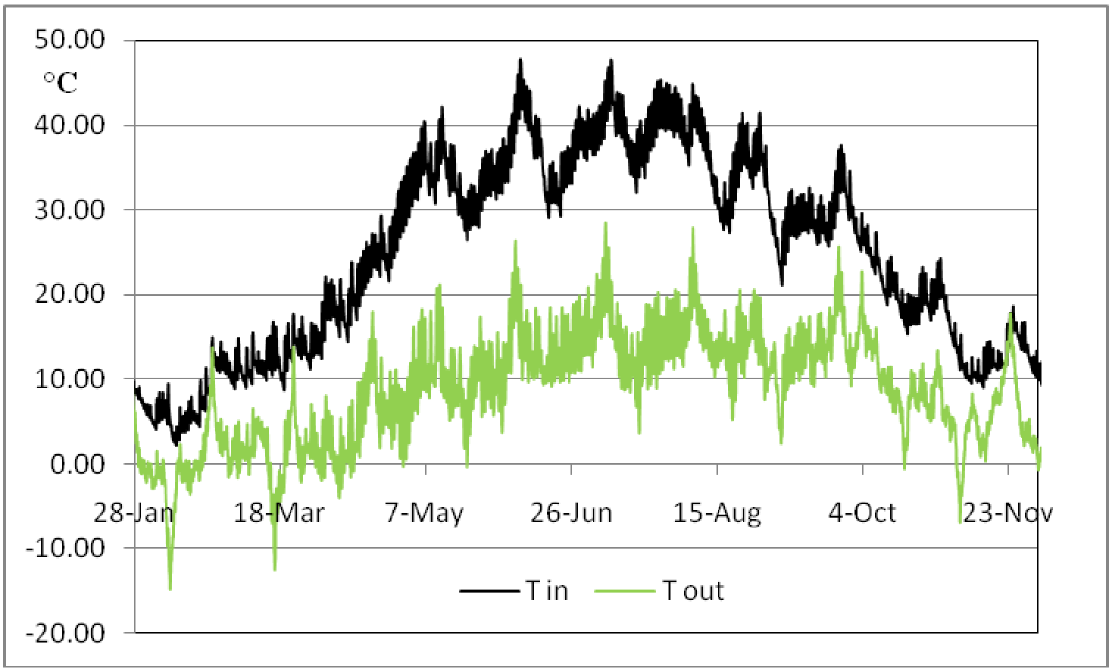
The building is the same as described in Section 4.3.1. Start temperature and relative humidity in the building were set to 20°C and 50% RH respectively. The simulations were run with the climate file for Göteborg. Changes or additions of the input are described in a separate chapter.

8.2 Free running temperature simulation of the building

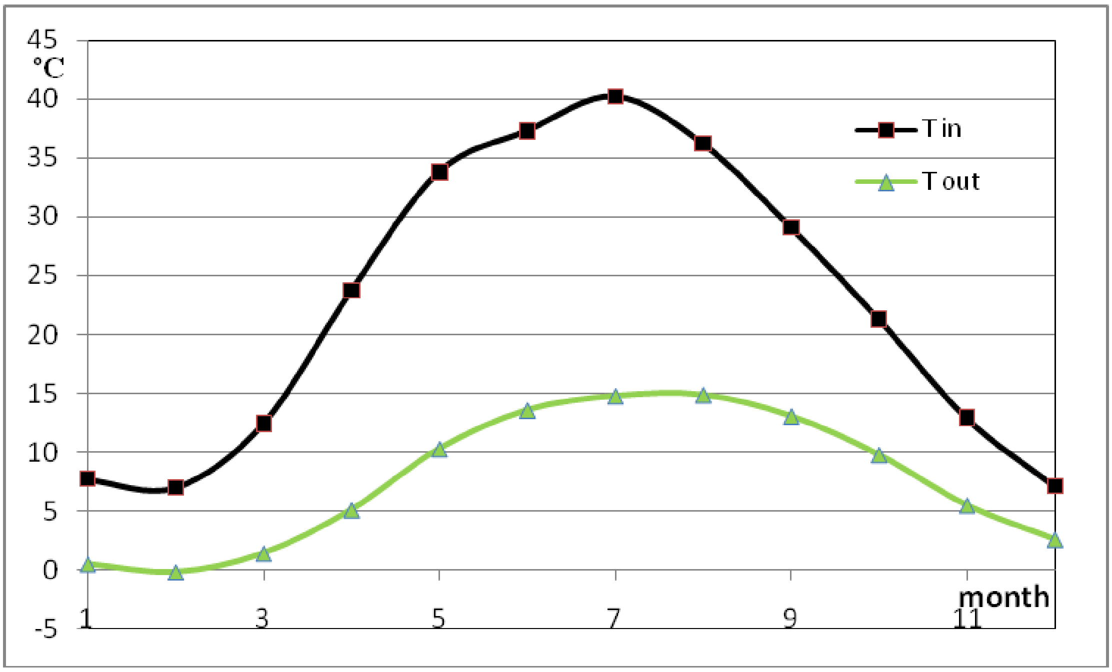
The results of the simulation of the climate in the building without installations and internal loads are presented below.

8.2.1 Temperature

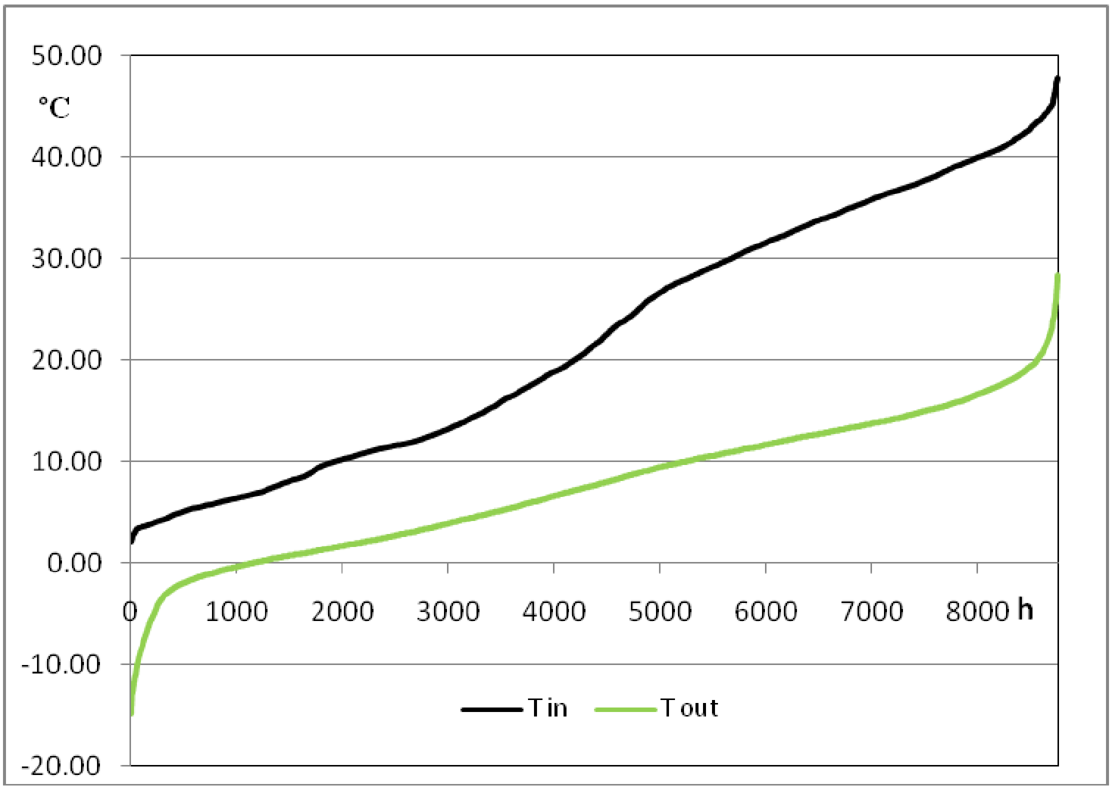
Figure 8.2 shows the simulated indoor temperature together with the outdoor temperature used as input. In a) over the year, b) as monthly mean values and in c) in a duration diagram.


50.00
°C
40.00
30.00
20.00
10.00
0.00
-10.00
-20.00
28-Jan
18-Mar
7-May
26-Jun
15-Aug
4-Oct
23-Nov
T in
T out

a)


45
°C
40
35
30
25
20
15
10
5
0
-5
1
3
5
7
9
11
month
T in
T out

b)



c)

Figure 8.2 Temperature in the building and outdoors for simulation of the reference building without heating system. a) Temperatures over a year. b) Monthly mean temperatures. c) Duration diagram.

In all the graphs in Figure 8.2 it can be seen that the indoor temperature follows the trend of the outdoor temperature though the deviation between the curves is larger during the warmer seasons. The indoor summer temperature also appears to be very high. In a) it can be seen that the indoor temperature rises well above 40°C for warm days (the maximum temperature is 47.8 °C). b) and Table 8.1 show that also the monthly mean temperatures are very high for the warm months. Looking at c) the indoor temperature is above 20°C more than 50% of the year.

Table 8.1 Monthly mean temperatures

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
T_{out}	0.5	-0.2	1.4	5.1	10.3	13.6	14.8	14.9	13.1	9.8	5.5	2.6
T_{in}	7.7	7	12.4	23.7	33.8	37.3	40.2	36.2	29.1	21.3	12.9	7.1

Due to the combination of a well-insulated building with big glass areas and a flat roof the temperatures are not surprising. These factors create a building that is easily affected by solar radiation. The glass parts let radiation energy in and the insulation prevents the indoor heat to escape through transmission (which also keeps the building warm during night time and days when the solar radiation is strong even if the outdoor temperature is cold). The flat surface of the roof makes it exposed to direct sunlight all day (in comparison to a tilted or horizontal surface that is shadowed during parts of the day). A closer look at the temperature for the week containing the warmest outdoor temperature is shown in Figure 8.3.

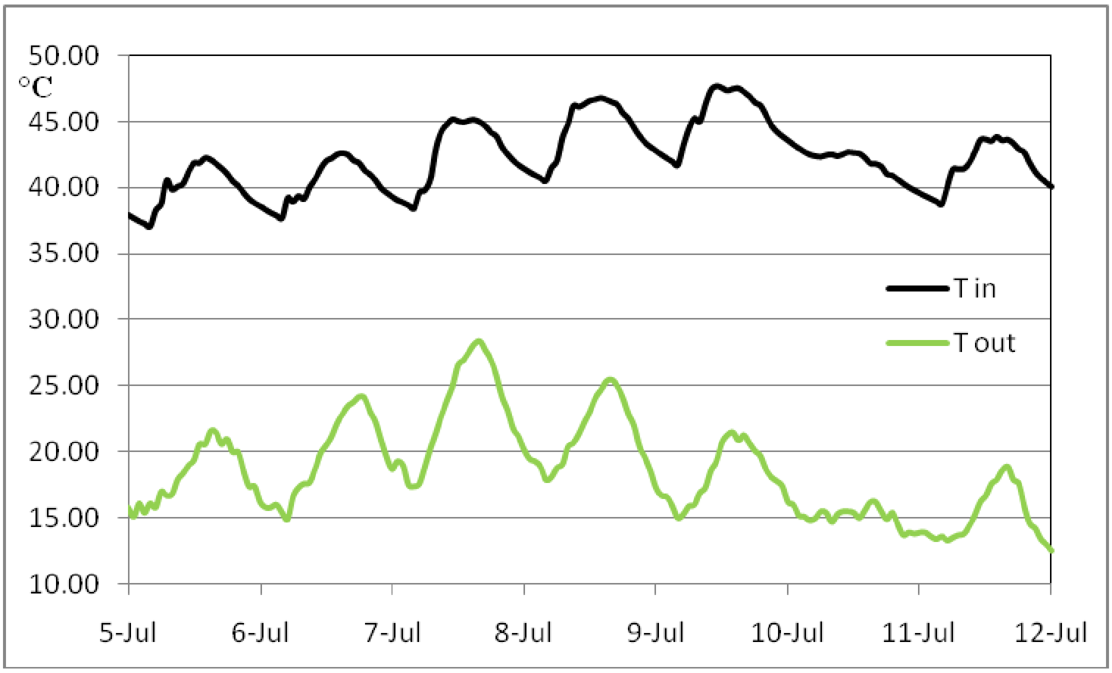


Figure 8.3 Temperature outdoors and in the building for cold simulation during 7-13 June.

The figure shows, in addition to the very high indoor temperatures, that the heat peaks occur indoors before they occur outdoors. This is due to the quicker heating of the limited air volume inside the building compared to the outdoor air. Since most of the glass in the building is placed in the eastern façade the morning sun can be used as help for warming the building after the night. The building's combination of a small air volume inside an insulated envelope makes it affected by the heat through a window also when the solar radiation is not very strong; the outdoor air reaches its peaks during the afternoon.

Also during the week containing the coldest outdoor temperature of the year the impact of solar radiation is clearly visible see Figure 8.4. Note that the temperature indoors never drops below 0°C, Figure 8.2 b).

The very visible impact of solar radiation should to be considered before constructing this type of building, especially in sun dense climates.

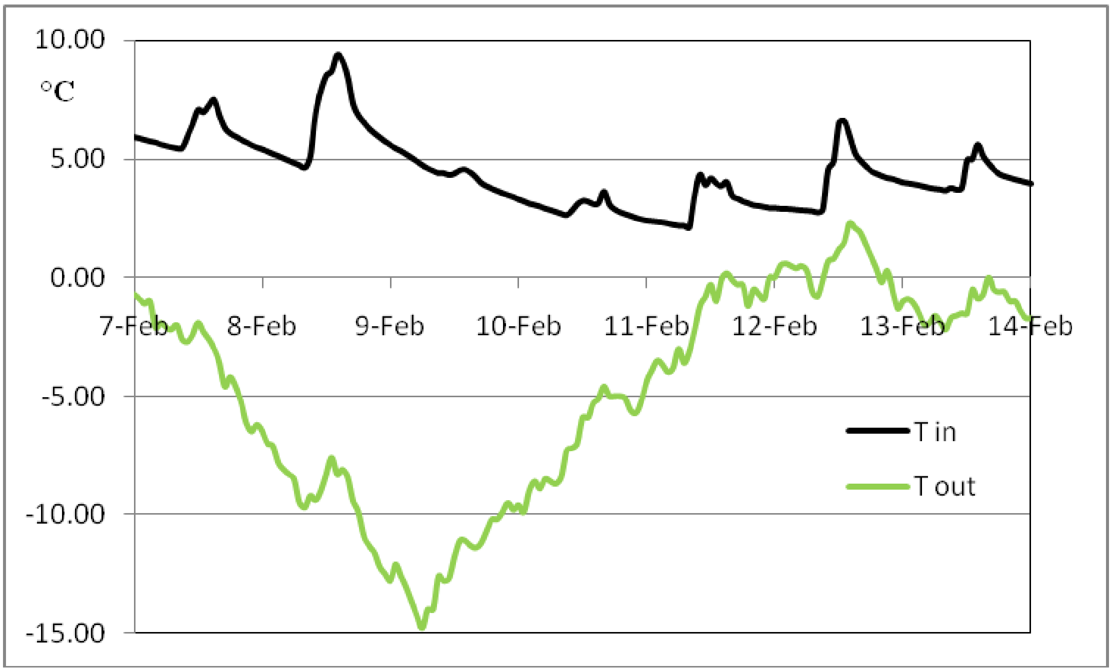
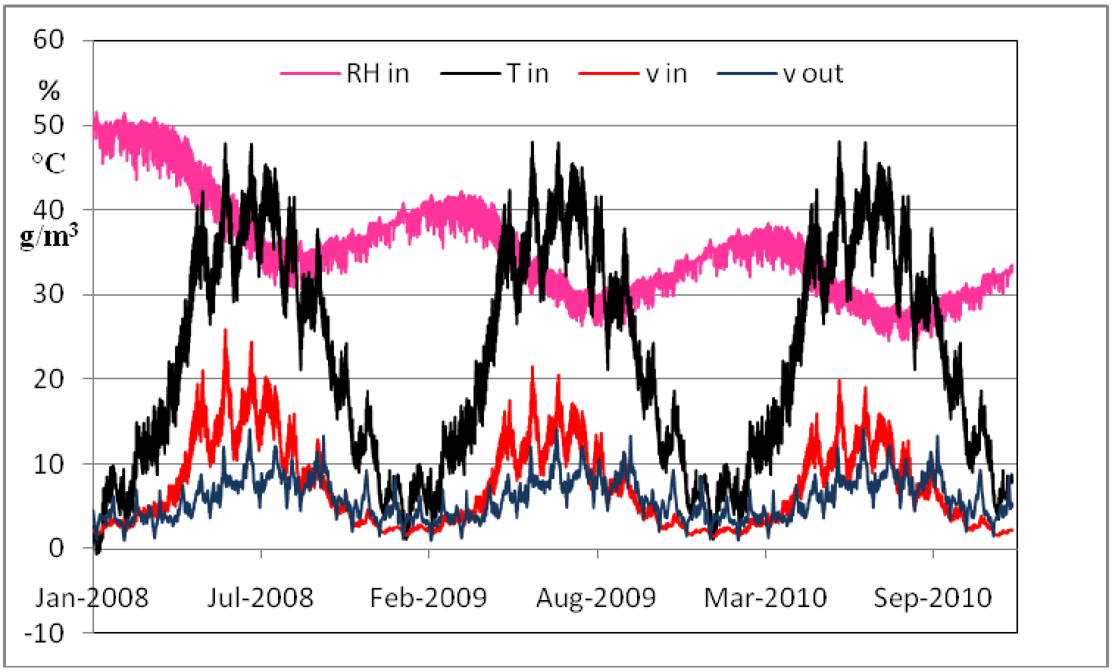


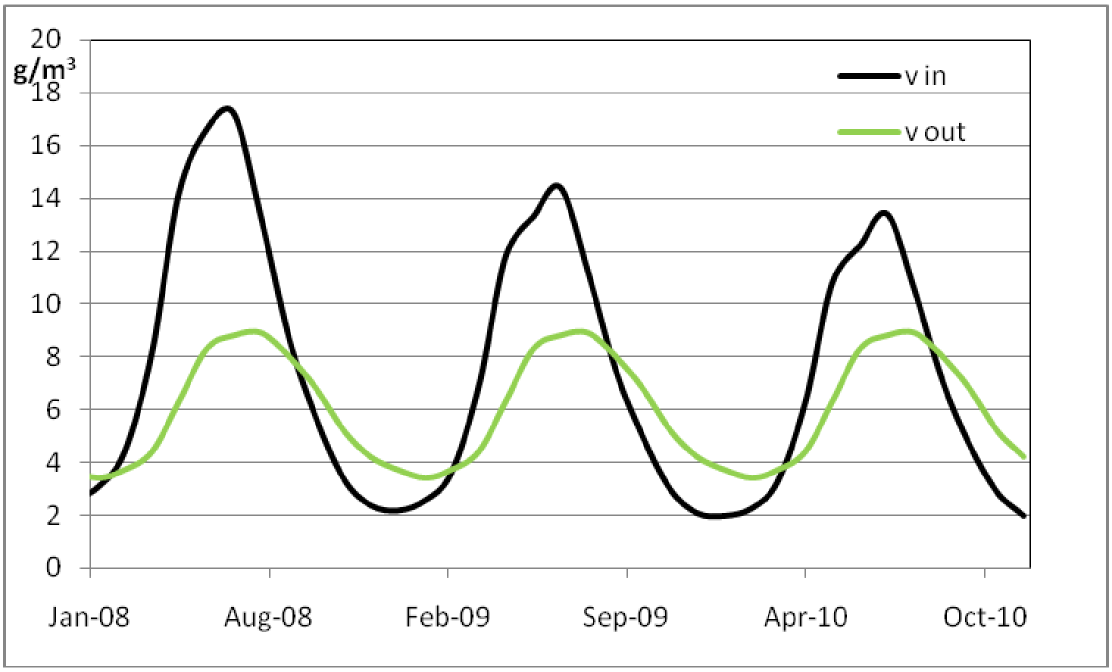
Figure 8.4 Temperature outdoors and in the building for cold simulation during 6-12 February

8.2.2 Relative humidity and vapor content

In order to see the behavior of the humidity in the building a simulation (free running) over three years was run. To decrease the initial vapor content the starting temperature was set to 0°C (with the initial RH kept at 50%). The results of the simulation can be seen in Figure 8.5 below.



a)



b)

Figure 8.5 a) Relative humidity, temperature and vapor content for the air in the building during three years. b) Monthly mean vapor content indoors and outdoors over three years.

Figure 8.5 a) shows the monthly mean vapor contents outdoors and indoors. This figure shows clearly that the vapor content indoors is not mainly a result of the vapor content in the outdoor air in that the indoor curve reacts ahead of the outdoor one. The dominating factor behind the behavior of the vapor inside the building is most probably the building aiming to get in balance with the vapor content in the ground. Vapor from the ground rises into the building during the winter (when the content is low inside the building/when the house is colder than the ground) and a part of it goes back during the summer (when the house is warmer than the ground) and the rest goes out to the ambient air.

8.3 Building with installations and internal heat loads

The effects of installations and people were studied through three different simulations.

1. *Heated* with heating system and ventilation
2. *Int. loads* with heating, ventilation, moisture and heat loads
3. *Vent* free running temperature simulation with ventilation
4. *(Vapor loads* with heating, ventilation and vapor loads)

The heating system switched on when the temperature in the building was lower than 20°C. The ventilation rate was held constant at 0.5 air changes/hour. The internal loads that were used are those listed in Table 8.2 (same as in Table 4.5)

Table 8.2 Internal loads in the building

Time	Moisture gain [g/h]	Heat gain [W/h]

0-6	25	200
6-8	400	300
8-16	25	200
16-22	200	400
22-24	25	200

8.3.1 Energy consumed for heating

The simulation without heat loads gave energy consumption for heating of 5535kWh (87.9 kWh/m2, year). Simulation with internal loads gave 4462kWh (70.8 kWh/m2, year), which is almost 20% less. Hence the internal heat loads have a very visible impact on the temperature in the building. This is, together with the effect of adding the heating system and ventilation, presented below.

8.3.2 Temperature

The continuous lines in Figure 8.6 show the effect of adding heating and ventilation to the building. The dashed line shows the indoor temperature when the internal loads are added. The plotted monthly mean values can be found in Table 8.3 further down this chapter.

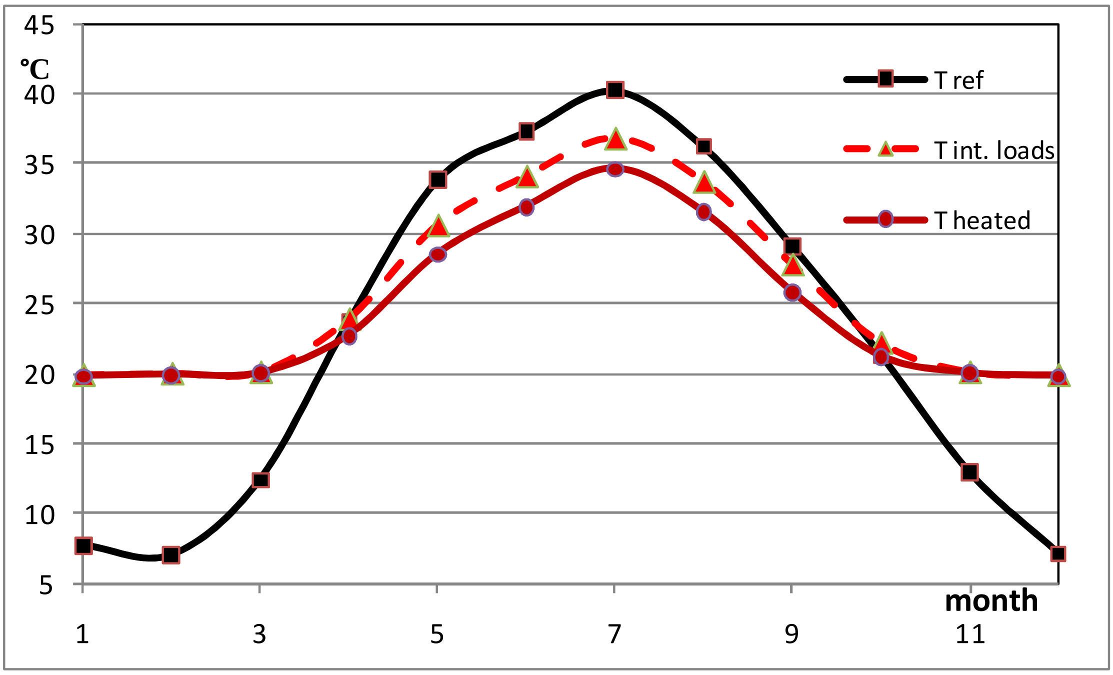


Figure 8.6 Monthly mean temperatures outdoors and in the building with and without heating system

Comparing the temperatures for the unheated reference case to the heated building it can be seen that the ventilation lowers the indoor temperature very visibly during summer. The effect of the ventilation system can be seen in Figure 8.7. Comparing the temperatures for the heated building with and without internal loads the effect of the heat loads is a rise of about 2°C.

The use of outdoor air for ventilation relates the cooling effect to the difference between the indoor and outdoor temperature, which is very clearly visible when comparing the deviation between the unventilated reference curve and the ventilated free running temperature curve in Figure 8.7. The difference in July is about 5°C compared to less than 1°C in December. Resulting in the heating of the building increases the cooling effect of the ventilation during the winter.

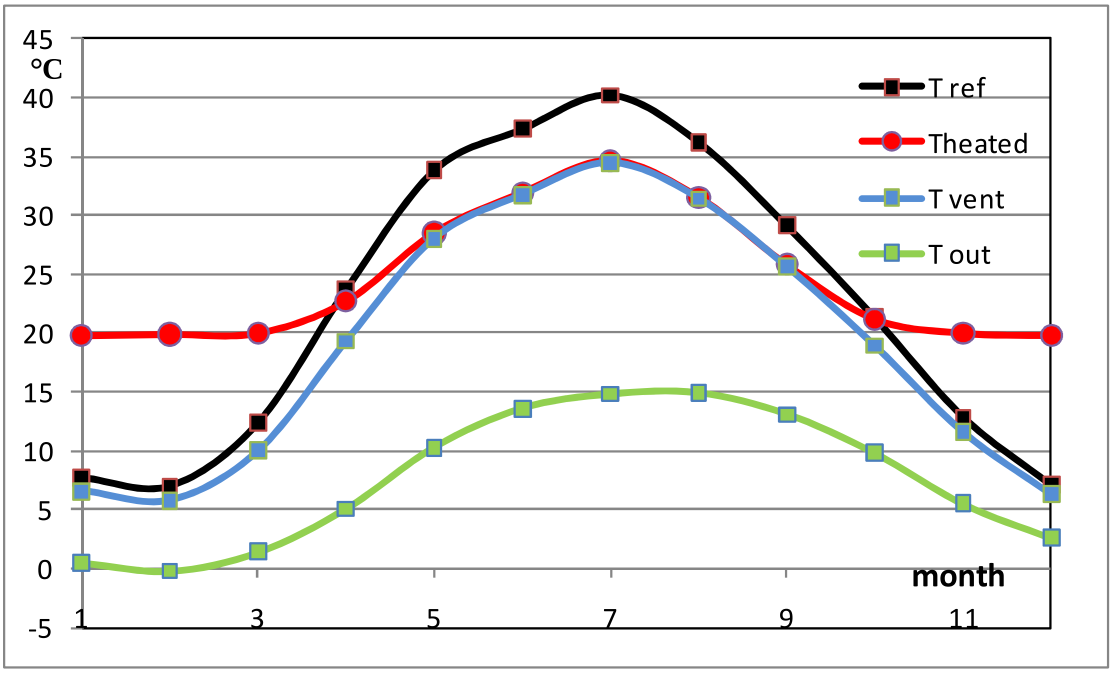


Figure 8.7 Effect of the ventilation on the monthly mean temperatures

Table 8.3 Monthly mean temperatures

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
T_{out}	0.5	-0.2	1.4	5.1	10.3	13.6	14.8	14.9	13.1	9.8	5.5	2.6
T_{ref}	7.7	7.0	12.4	23.7	33.8	37.3	40.2	36.2	29.1	21.3	12.9	7.1
T_{vent}	6.6	5.8	10.0	19.3	28.0	31.7	34.4	31.4	25.6	18.9	11.6	6.3
T_{heated}	19.8	19.9	20	22.7	28.5	31.9	34.6	31.5	25.8	21.2	20	19.8
T_{heat} loads	19.9	20.0	20.1	23.9	30.6	34.1	36.8	33.7	27.8	22.2	20.1	19.9

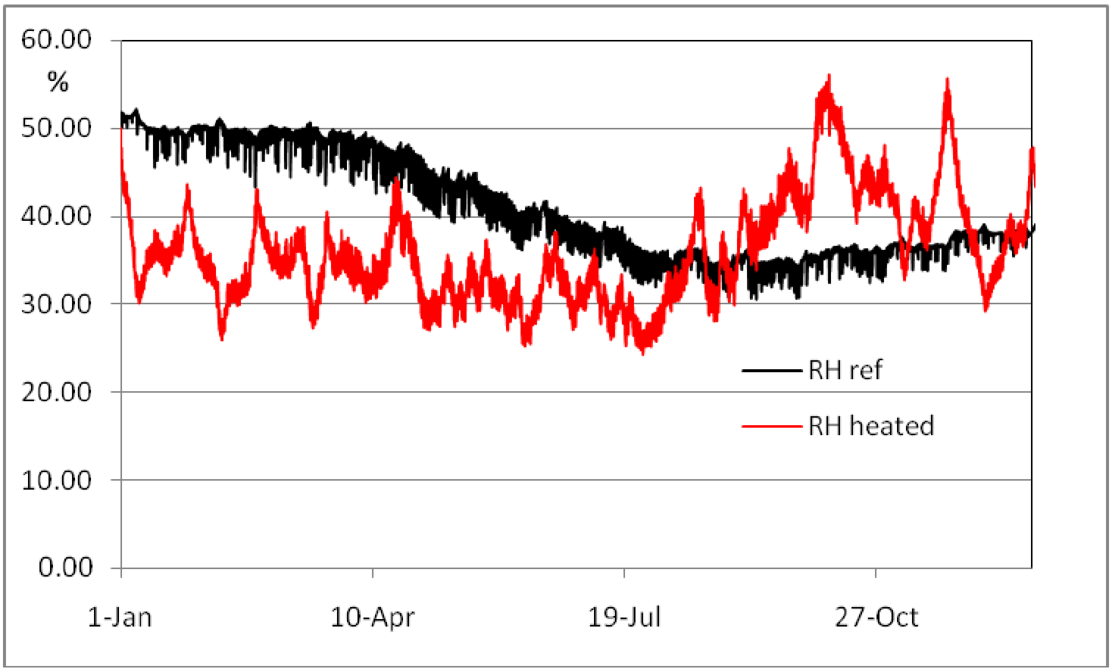
8.3.3 Relative humidity and vapor content

Figure 8.9 and Table 8.4 show the monthly mean vapor content over two years. The vapor content in the heated building is very close to the vapor content in the outdoor air and the decrease, that is so visible for the reference case, is now very small (there is no difference at all between the second and third year). The use of untreated outdoor air in the ventilation and the fact that diffusion is a slow process compared to the air change rate of the ventilation explains the differences. The vapor loads add about 1g/m^3.

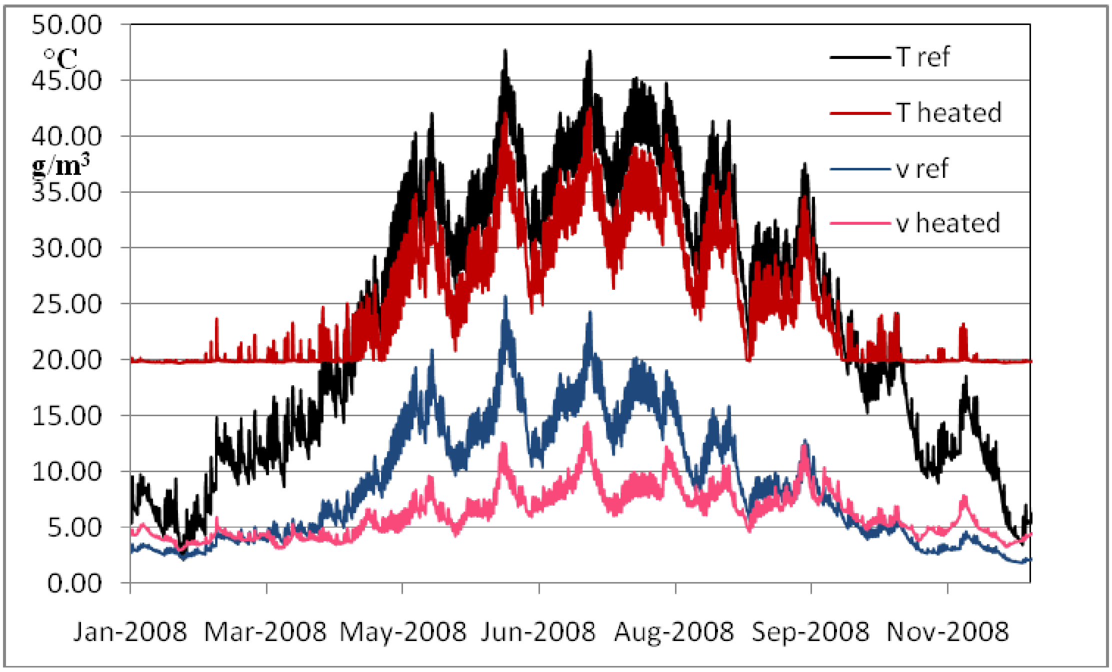
Table 8.4 Monthly mean vapor content

	v_{out} [g/m^3]	v_{ref} [g/m^3]	v_{heated} [g/m^3]	$v_{vapor\ loads}$ [g/m^3]
Jan-08	3.7	2.5	4.6	5.3
Feb-08	3.4	3.1	4	4.8
Mar-08	3.7	4.4	4	5
Apr-08	4.4	8.2	4.8	5.8
May-08	6.3	14.2	6.5	7.6
Jun-08	8.3	16.6	8.6	9.7
Jul-08	8.8	17.2	9.1	10.2
Aug-08	8.9	13.2	8.5	9.7
Sep-08	8	8.7	7.4	8.5
Oct-08	6.8	5.7	6.5	7.4
Nov-08	5.2	3.4	5.2	6.1
Dec-08	4.2	2.4	4.4	5.3
Jan-09	3.7	2.2	4	5
Feb-09	3.4	2.6	3.7	4.7
Mar-09	3.7	3.6	3.9	4.9
Apr-09	4.4	6.9	4.6	5.8
May-09	6.3	11.8	6.4	7.6
Jun-09	8.3	13.3	8	9.1
Jul-09	8.8	14.4	9	10.1
Aug-09	8.9	11.2	8.5	9.6
Sep-09	8	7.5	7.4	8.4
Oct-09	6.8	5	6.5	7.4
Nov-09	5.2	3	5.1	6.1
Dec-09	4.2	2.1	4.4	5.3

Focusing on the relative humidity in the building Figure 8.10 a) shows the difference in the behavior for the relative humidity between the reference case and the heated building and b) the curves for temperature and vapor content that can be used for explaining the difference.



a)



b)

Figure 8.10 Moisture in the building with and without heating system a) Relative humidity. b) Temperatures and vapor content.

The behavior of the reference curve is explained above. The effects of the ground is less visible for the heated curves since the ventilation removes some of the vapor indoor and the vapor load adds additional moisture.

9 Simulation of the building in the greenhouse

Adding the greenhouse to the model creates a new climate zone. Now the climate in the building is affected by the climate in the greenhouse, which in its turn is affected, by the outdoor climate (and in reality slightly by the climate in the building, but this is not modeled). Figure 9.1 shows the principle. Note that here the intensity in the sunlight is reduced through the transmittance of the greenhouse (τ_{gh}) before it reaches the walls and windows in the building. The intensity of the radiation that enters the building through the windows is therefore reduced first through the greenhouse's transmittance and then through the transmittance of the windows.

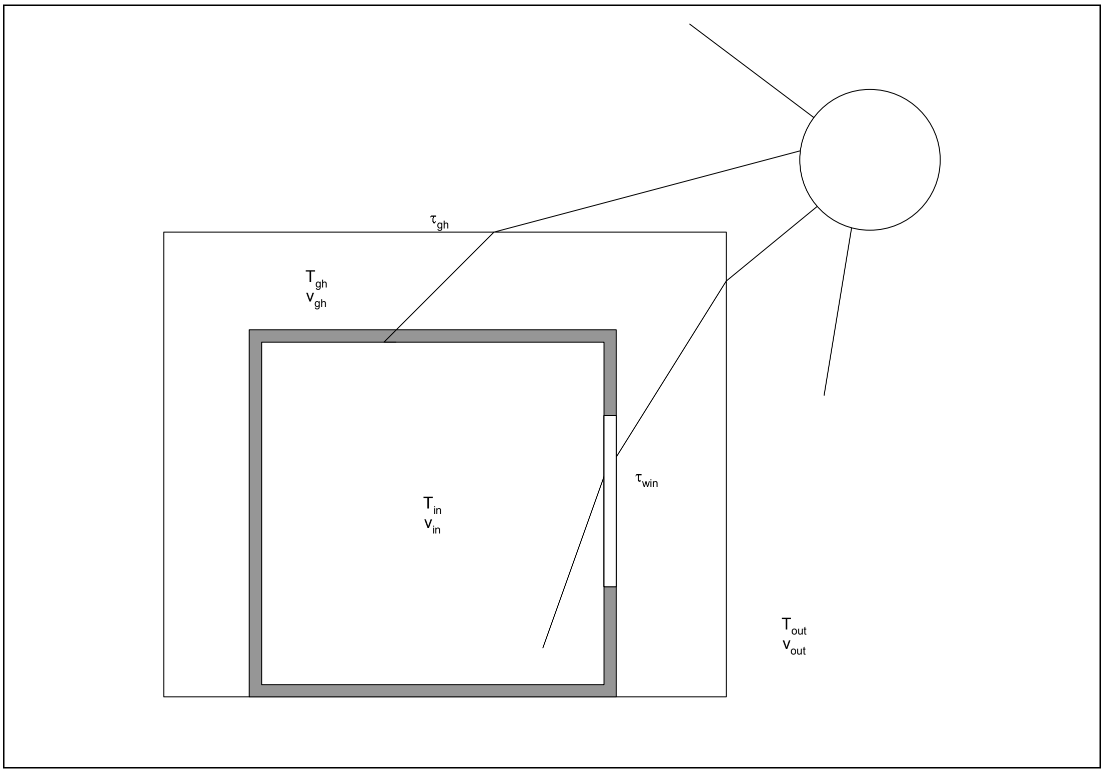


Figure 9.1 Schematic picture of the model of the building standing in the greenhouse.

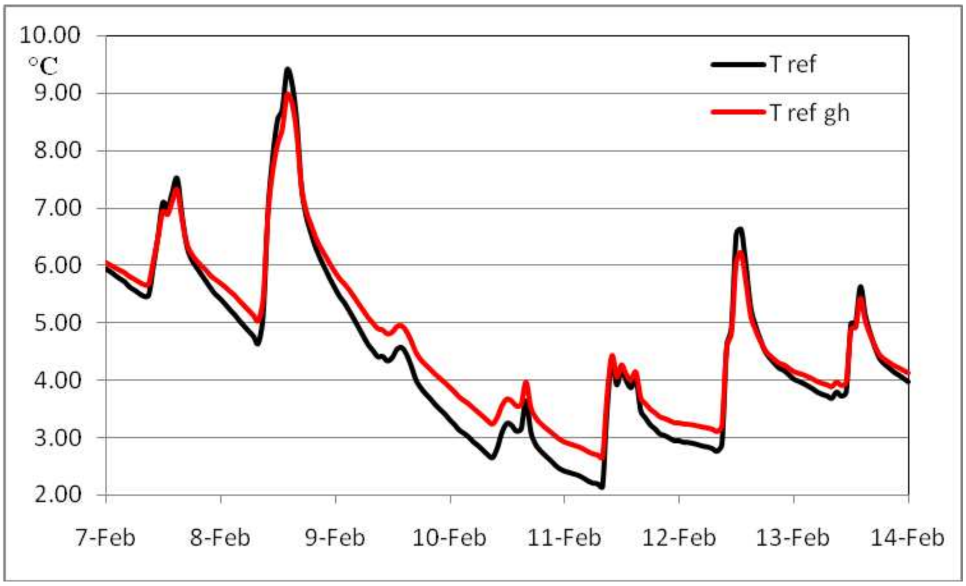
9.1 Input for the case building in the greenhouse

For the building only those changes are made that follows from the placement in the greenhouse (reduced sun intensity and changed surrounding temperature).

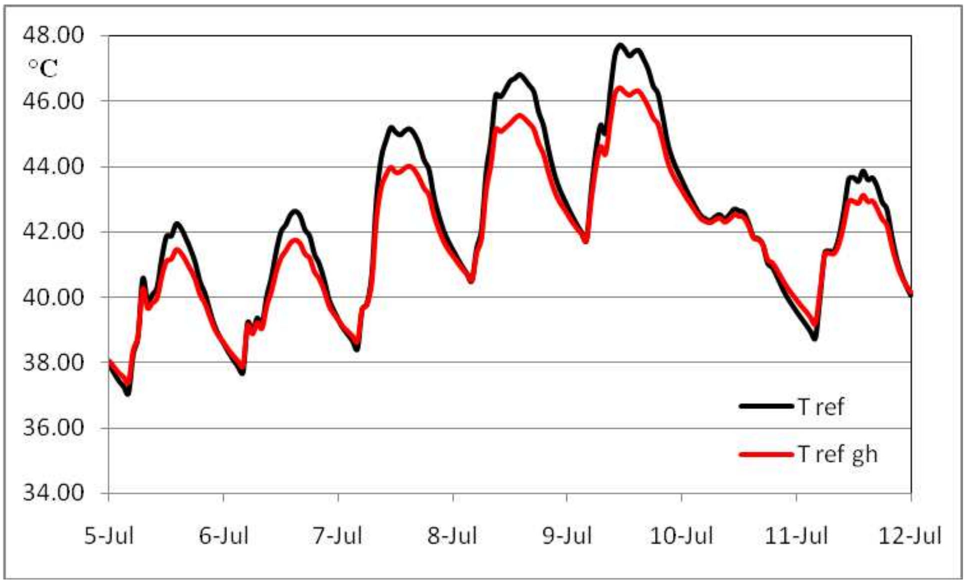
The greenhouse is the same as described in Section 4.3.2 and simulated in Chapter 6. No other ventilation than that through the gap at the bottom is used. The start temperature and relative humidity are set to 0°C and 80% respectively.

9.2 The greenhouse's impact on the climate in the building

Adding the greenhouse to the model of the building actually increases the energy consumed for heating somewhat, from 5535 kWh/year (88kWh/m^2, year) to 5576 kWh/ year (88.5 kWh/m^2). Taking a look at the temperature results from the free running simulations for the weeks with the minimum and maximum outdoor temperatures, Figure 9.2 below, it appears that the greenhouse helps to keep the temperature in building more comfortable, both the cold and warm week, generally warmer for the cold week and cooler for the warm week.



a)



b)

Figure 9.2 Temperature results for simulation of the building without heating system, with and without the surrounding greenhouse. a) for 6-12 February b) 7-13 July.

For the cold week this is due to the warmer surrounding temperature but as can be seen for the higher temperature peaks, where the building without the surrounding greenhouse is warmer, this effect is smaller than the effect of the reduced solar radiation. The reduced incoming solar radiation appears to be the reason both for the higher energy consumption and for the better indoor temperatures during the warm week. The fact that this is visible even for February, when the intensity of the solar radiation is not very strong, again shows how easily the sun affects the building. For the cold week the reduction is less than 0.5 degrees and only occurs for a few hours while for the warm week it is more than 1 degree and over longer periods. Taking a look at the difference in monthly mean temperatures, Table 9.1, this effect is visible even when the hours without sunlight are included in the calculations. The mean temperature for the building in the greenhouse is slightly colder for all months except those with the least solar radiation, November, December and January. Since the transmittance of the greenhouse glass works in both directions it also prevents some of the sky radiation during nighttime to occur, so the house inside the greenhouse is slightly warmer during the night than the building without greenhouse.

Table 9.1 Monthly mean temperatures for the building with and without surrounding greenhouse

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
T_{ref} [°C]	7.7	7	12.4	23.7	33.8	37.3	40.2	36.2	29.1	21.3	12.9	7.1
T_{gh} [°C]	8	6.7	12.2	23.1	33.4	37.1	40.1	36.3	29	21.2	12.9	7.2
Difference [°C]	0.3	-0.3	-0.2	-0.6	-0.4	-0.2	-0.1	-0.1	-0.1	-0.1	0	0.1

9.2.1 Relative humidity

In Figure 9.3 below results from the simulations of the relative humidity for the reference case and the building in the greenhouse are shown. Both the curves for the heated and unheated simulations show the same pattern for the reference building and the building in the greenhouse. The addition of the greenhouse seems to have no major impact on the behavior of the relative humidity in the building more than the one that follows from the temperature difference. The difference for the unheated simulations can be estimated from the colder summer temperatures for the building in the greenhouse.

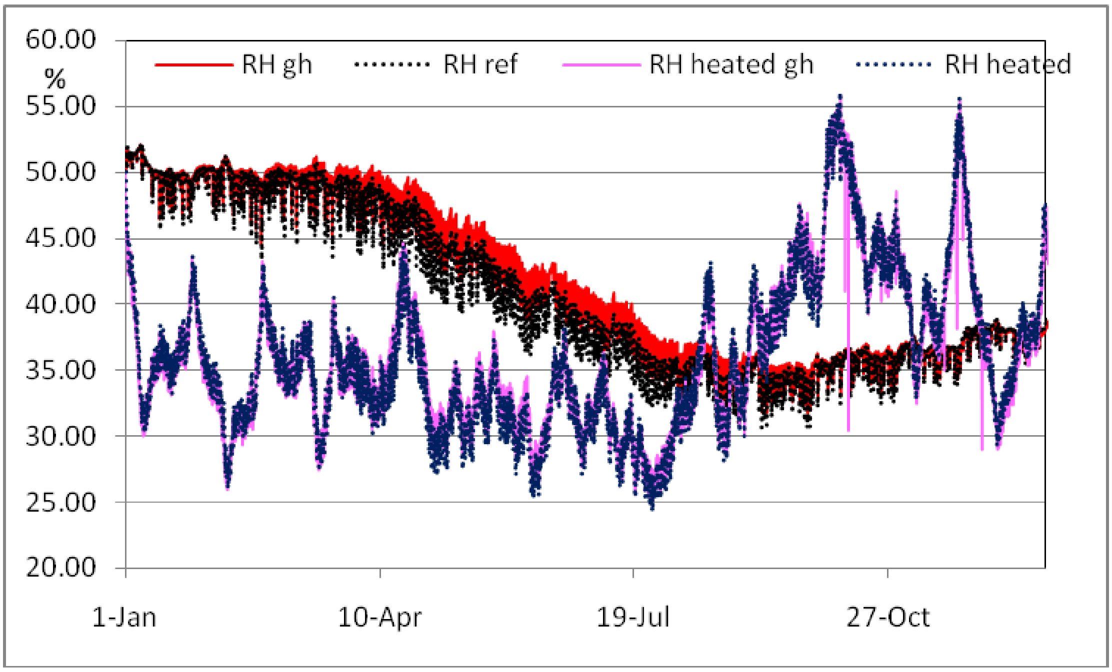


Figure 9.3 Relative humidity for the simulations of the building with and without greenhouse and with and without heating system.

9.3 Main conclusions from chapter 8 and 9

To summarize the most important conclusions from the simulations of the building with and without the surrounding greenhouse it can be said that the building is very easily affected by solar radiation. This causes the addition of the greenhouse to mainly have a temperature reducing effect of the indoor temperature in the building since the incoming solar radiation is reduced through the transmittance of the glass in the greenhouse. A heating effect of the temperature difference between the outdoor air and the greenhouse is only visible for those months when there is very little sunlight. However, the effect is small maximum +0.3°C. The result of the sensitivity to the solar radiation is that the indoor temperature can rise very high during the summer and this makes the ventilation of the building very important in order to keep the indoor temperature acceptable.

10 The impact of the choice of materials in the building when it is placed in the greenhouse

In order to evaluate the chosen design's suitability for being placed in a greenhouse the original building has been compared to two simple types of more traditional structures, a heavy structure made of concrete and insulation and a lightweight structure. Both of these structures were set to have the same U-value as the original building. In addition to those, also the effects of some minor (theoretical) changes in the design of the original building were simulated. In this first case the insulation was removed from the roof and in the second the aerated concrete in the walls and the expanded clay blocks in the roof were replaced by a concrete with w/c-ratio of 0.65. The energy needed for heating was evaluated together with the effect on the temperatures in the building.

10.1 Input

In designing the test buildings no consideration was taken to load carrying capacity since only the U-values and material properties were considered to be important for this schematic evaluation. Hence the walls and roofs in the structures with the same U-value as the original were assumed to be constructed as plain layers of materials with the thickness of the insulation layer adjusted to give the desired U-value. In the other structures the insulation was removed and the concrete material changed respectively. For all cases the windows, the doors and the floor design remained unchanged. Materials, thickness and lambda values for the different designs can be seen in table 10.1 below.

Table 10.1 Designs for U_{wall}= 0.22W/m^2,K, U_{roof}=0.21W/m^2,K and changes in the original design

Part	Design/material	d [mm]	λ [W/m,K]
	Original		
Wall	Aerated concrete	375	0.09
	Gypsum board	10	0.2
Roof	Concrete	30	1.5
	Insulation	150	0.04
	Blocks of expanded clay	250	0.3
	Heavy		
Wall	Cement mortar	10	1.2
	Insulation	163	0.04
	Concrete	100	1.5
Roof	Concrete	30	1.5
	Insulation	180	0.04
	Concrete	100	1.5
	Light		
Wall	Spruce	15	0.1
	Insulation	158	0.04
	Gypsum board	13	1.2
Roof	Spruce	15	0.1

	Insulation	175	0.04
	Gypsum	13	1.2
	Concrete		
Wall U=2.13W/m^2,K	Concrete	375	1.5
	Gypsum board	10	1.2
Roof U=0.24 W/m^2,K	Concrete	30	1.5
	Insulation	150	0.04
	Concrete	250	1.5
	Without insulation on the roof		
Roof U=0.98 W/m^2,K	Concrete	30	1.5
	Blocks of expanded clay	250	0.3

All simulations for energy calculations were made with an air change rate of 0.5 air changes per hour. Internal moisture loads are being included but no internal heat loads. The initial temperature in the buildings was set to 20°C.

10.2 Effect of the greenhouse on the energy consumption for heating for the different designs

In Table 10.2 below the simulated energy need for keeping the indoor temperature at 20°C during the heating period for the different designs is shown. The table first shows the result for the building alone and then for the building standing in the greenhouse. Furthermore it shows the differences in consumed heating energy for the with/without greenhouse case for each design and the differences between the reference building in the greenhouse compared to the other designs in the greenhouse.

Table 10.2 Energy consumption for different designs

	Ref	Heavy	Light	Concrete	Without roof ins.
Building [kWh/m^2,year] (kWh/year)	87.9 (5535)	87.1 (5490)	90.6 (5710)	271.9 (17130)	150.0 (9447)
Building in greenhouse [kWh/m^2,year] (kWh/year)	88.6 (5579)	111.3 (7011)	96.8 (6096)	208.1 (13110)	133.2 (8390)
Difference in consumed energy Building in greenhouse-building, (kWh/m^2, year)	0.7 +0.8%	24.2 +27.8%	6.2 +6.8%	-63.8 -23.5%	-16.8 -11.2%
Difference from reference case in greenhouse, (kWh/m^2, year)	-	22.7 +24.8%	8.2 +9.3%	119.5 +134.9%	44.6 +50.3%

The table shows that the reference case is the most energy efficient, even compared to the designs with the same U-value. It also shows that for all the designs with the same U-value the addition of the greenhouse causes a greater demand for heating than for the cases without greenhouses. Looking at the new designs with equal U-value during the cold week, Figure 10.1, it can be seen that the temperature always is warmer for the case without greenhouse (compared to the reference building where the "without greenhouse case" was only warmer for the peaks during this week, chapter 8.3). This is most likely due to the same reason as before-the reduction of the solar radiation.

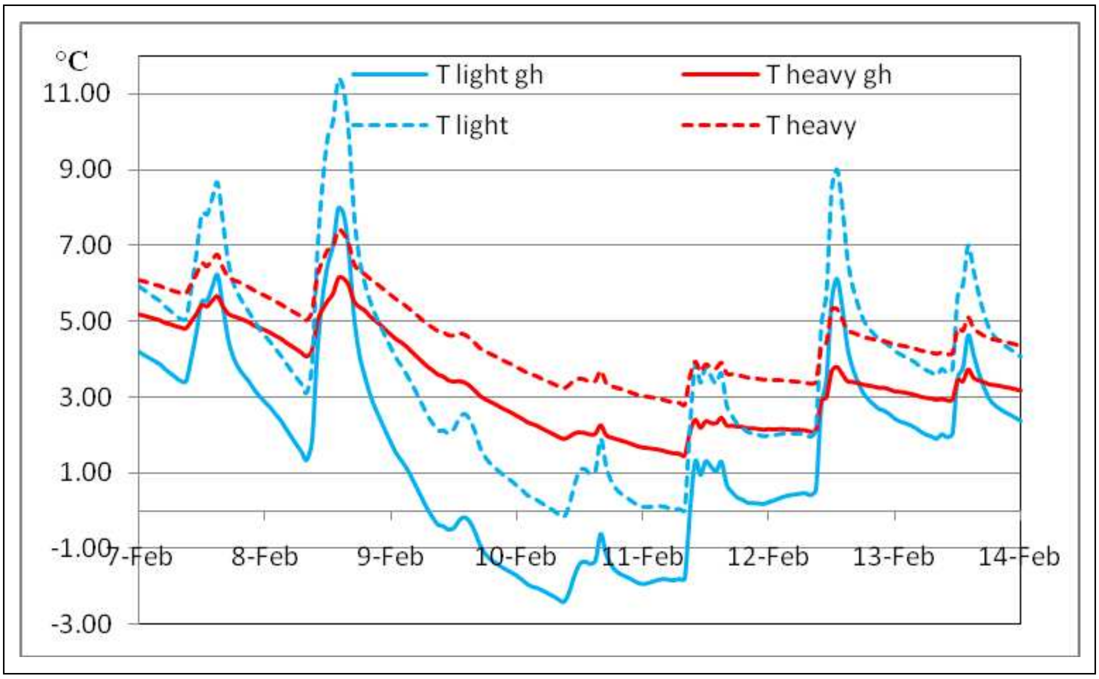


Figure 10.1 Temperatures in the building with and without greenhouse during the cold week. Designs with equal U-value.

For the two designs with higher U-values all the energy consumptions are markedly higher than for the reference building. Through the equation for static transmission losses, equation 10.1 below, it can be seen that a higher U-value will increase the heat flow hence those results were expected.

$$Q = UA(T_{in} - T_{out}) \tag{10.1}$$

A higher U-value also makes the impact of solar radiation smaller since this additional heat now more easily can flow through the building envelope. This would make the buildings more sensitive to the temperature differences between the outdoor air and the air in the greenhouse than the reduction of inflowing solar radiation and looking at Figure 10.2 this can be seen. The buildings now are warmer when placed in the greenhouse; even though the reduction of solar energy still can be seen in the peak heights.

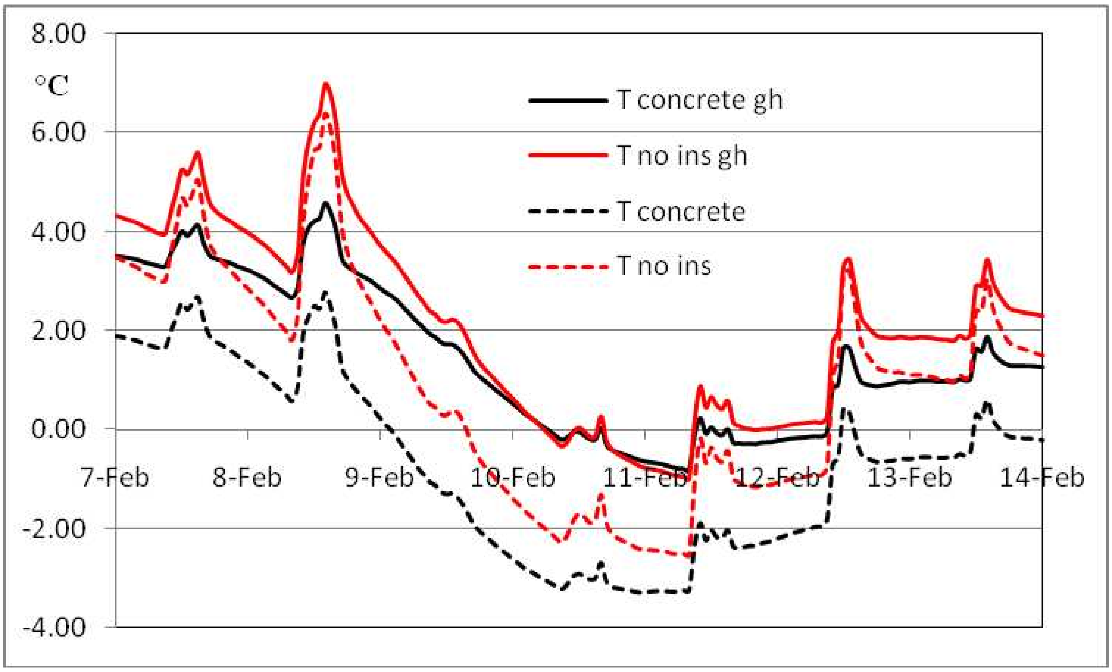


Figure 10.2 Temperatures in the building for changes in the original design, with and without the greenhouse during the cold week.

This led to an energy saving effect of the greenhouse of 24% for the building with concrete walls and 11% for the building without roof insulation.

The warming effect of the greenhouse in Figure 10.2 is almost 3°C which is much higher than the difference between the outdoor and greenhouse temperature for this week shown in Figure 10.3. Also for the design without roof insulation the effect of adding the greenhouse is clearly noticeable. The evaluation of the temperature effects of the design type and the placement of the building in the greenhouse will continue in the next chapter.

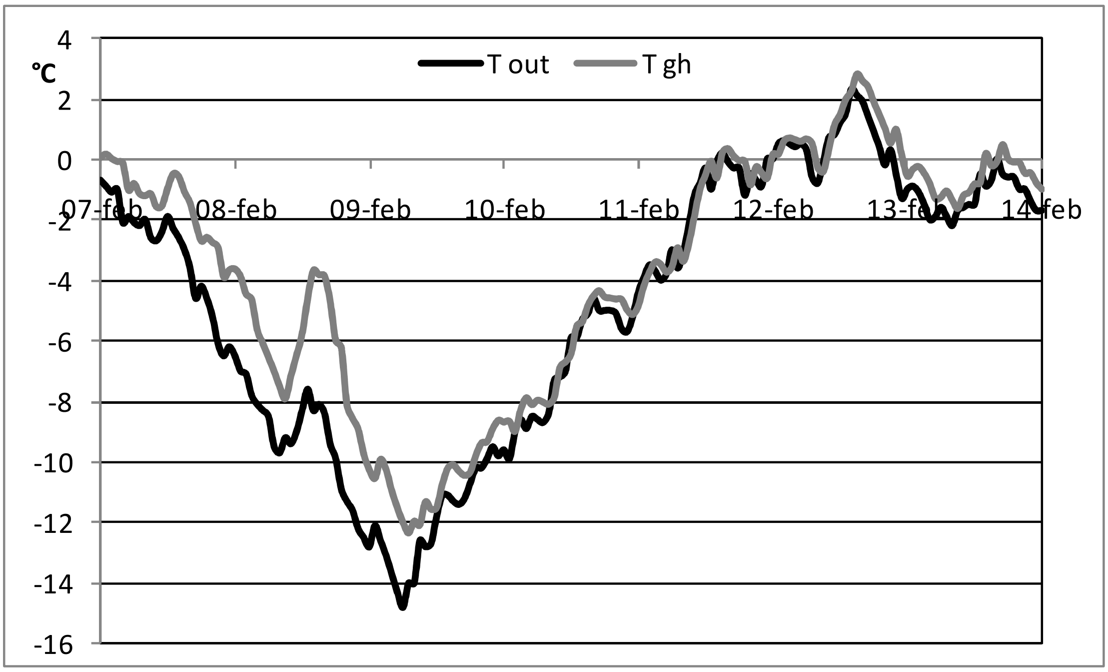


Figure 10.3 Temperatures in the building for changes in the original design, with

and without the greenhouse during the cold week.

The temperature effects are further discussed in chapter 10.3 and the explanation of why the buildings with equal U-value have different energy consumptions is given in chapter 11.

To summarize the effects on the energy consumption for heating it can be said that if the greenhouse is going to have a positive effect on the energy consumption for heating a design with high U-value shall be used but looking at the comparison for the energy used to heat the building (last row in Table 10.1) the original building is the best. The energy consumption of the reference building is relatively low. To reduce it heat recovery has to be used in the ventilation system.

10.3 Indoor temperatures for the different designs

Low energy use for heating is good but the buildings response to warm outdoor temperatures should also be considered when choosing the most suitable design. For comfort, and energy saving if cooling is to be used, it may be worth considering a slight increase in heating energy in order to avoid high indoor temperatures during summer.

In this section first the indoor temperatures for the buildings inside the greenhouse will be compared and second the effect of placing the different types in the greenhouse. In Table 10.3 the monthly mean temperatures in the building are listed for the different designs with and without the surrounding greenhouse. Those numbers are used as the basis for Figure 10.4 and 10.5.

Table 10.3 Indoor temperatures for the different designs with and without surrounding greenhouse

	Ref	Ref gh	Heavy	Heavy gh	Light	Light gh	Concrete	Conc gh	No ins	No ins gh
Jan	7.7	8	8	7	6.3	5.1	4.2	5.7	4.9	5.7
Feb	7	6.7	7	5.9	7.5	5.3	2.7	4.1	4.6	5.5
Mar	12.4	12.2	12.3	10.5	12.7	9.4	5.9	8.1	8.8	10.2
Apr	23.7	23.1	22.2	19.4	24.3	18.4	12	15.4	17.6	20.1
May	33.8	33.4	33.8	29.8	34.5	26.8	19.4	24.3	26.4	30.3
Jun	37.3	37.1	37.3	33.7	38.2	30.5	23	28.2	30.1	34.5
Jul	40.2	40.1	40.2	36.4	41.1	32.9	25.1	30.7	32.5	37.1
Aug	36.2	36.3	36.6	33.1	36.1	29.7	23.4	28.3	29.1	32.9
Sep	29.1	29	29.5	26.6	29	24	19.3	22.9	23.5	25.8
Oct	21.3	21.2	21.7	19.4	20.4	17.2	14.5	16.9	16.8	18.1
Nov	12.9	12.9	13.2	11.8	12.4	10.4	8.5	10.2	10	10.7
Dec	7.1	7.2	7.3	6.4	6.6	5.5	4.1	5.3	5	5.5

10.3.1 Temperatures for the designs in the greenhouse

Figure 10.4 shows the monthly mean temperatures for the designs when they are placed inside the greenhouse.

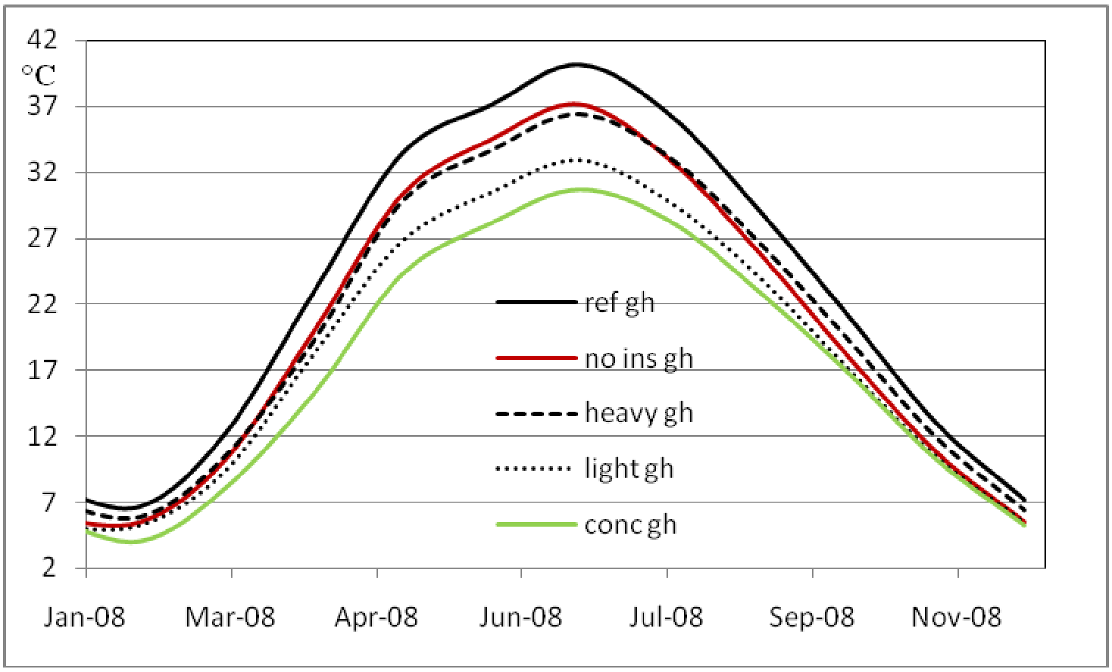
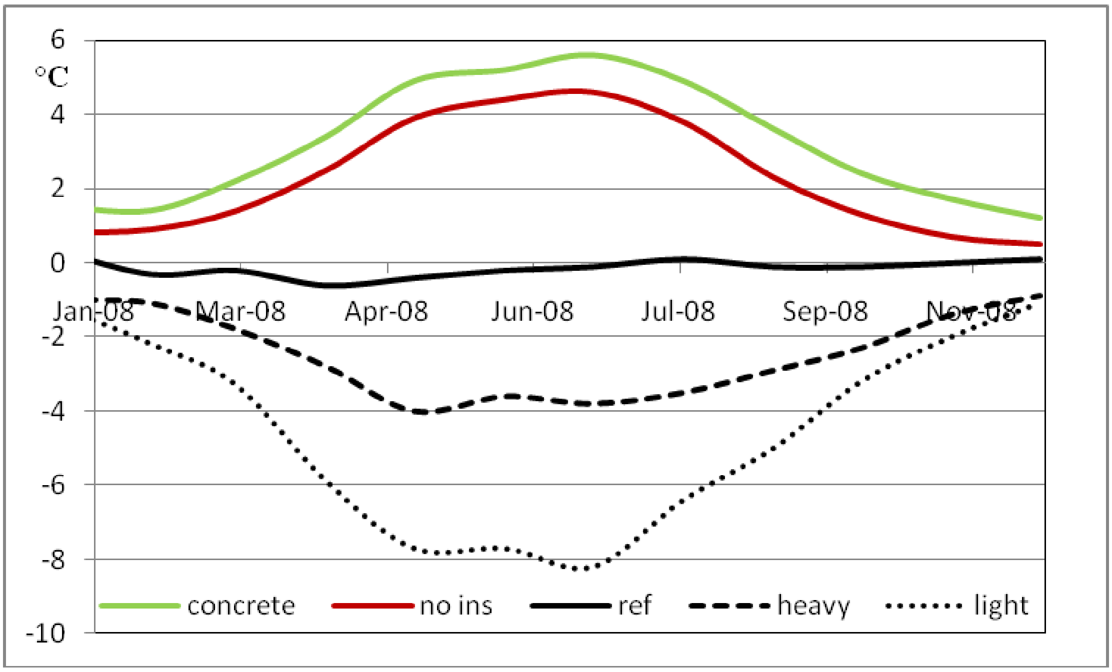


Figure 10.4 Indoor temperatures for the buildings in the greenhouse.

In the figure it can be seen that the reference building is the warmest and the concrete building the coldest throughout the whole year. This is well in line with the results from the energy comparison. It also shows that the difference in temperature from the original to the other buildings is larger during summer than during winter. Though the concrete design in this thesis is very hypothetical it clearly shows what difference can be obtained with different structures. The temperature difference between the original and the concrete design for July is more than 10^{o}C. The lightweight design, that appears to be the second coldest design, had an energy increase of 10% from the reference case. The main reason to the lowered monthly mean temperature for this design is the lower temperature during nighttime, which can be comfortable during summer; the daytime temperature is sometimes closer to the reference building's than the one created in the heavy design. See Figure 10.5 b).

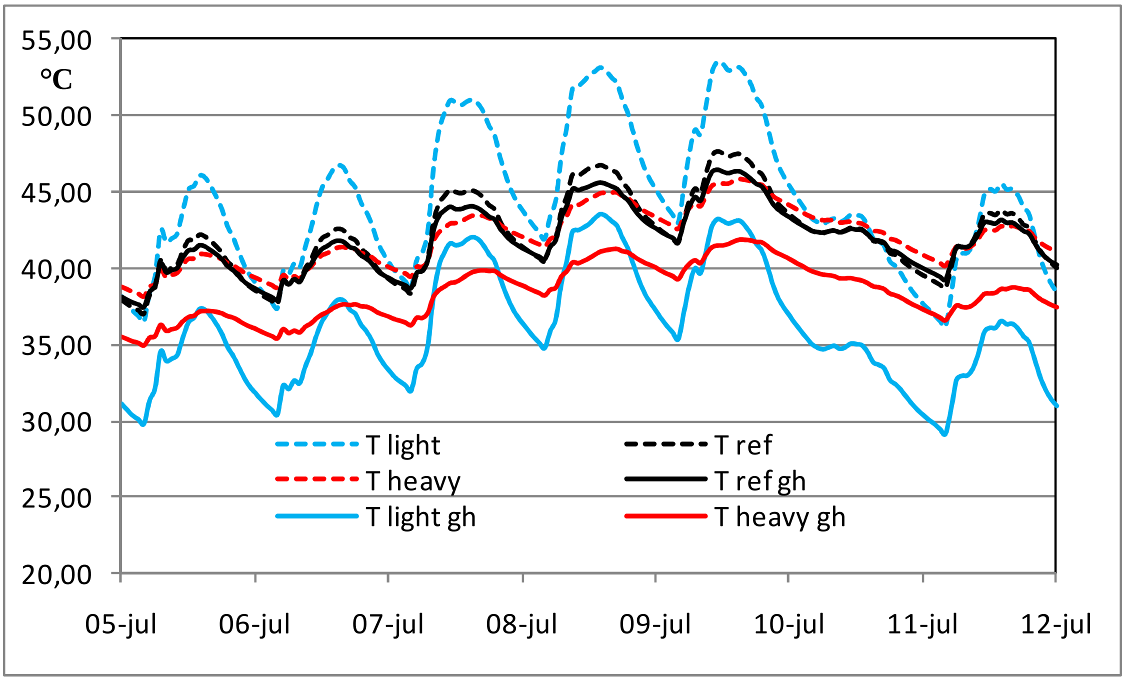
10.3.2 The effect of placing the buildings in the greenhouse

As it has been seen in the section about energy, 10.2 above, the greenhouse has different effects on different buildings. Those with high U-value get colder while the other two get warmer. Figure 10.5 a) show the differences in monthly mean temperatures for the buildings placed in the greenhouse compared to standing alone, T_{gh}-T_{ref}, while b) and c) show the differences for the new designs during the warm week.



6
°C
4
2
0
-2
-4
-6
-8
-10
Jan-08
Mar-08
Apr-08
Jun-08
Jul-08
Sep-08
Nov-08
concrete
no ins
ref
heavy
light

a)



55,00
°C
50,00
45,00
40,00
35,00
30,00
25,00
20,00
05-jul
06-jul
07-jul
08-jul
09-jul
10-jul
11-jul
12-jul
T light
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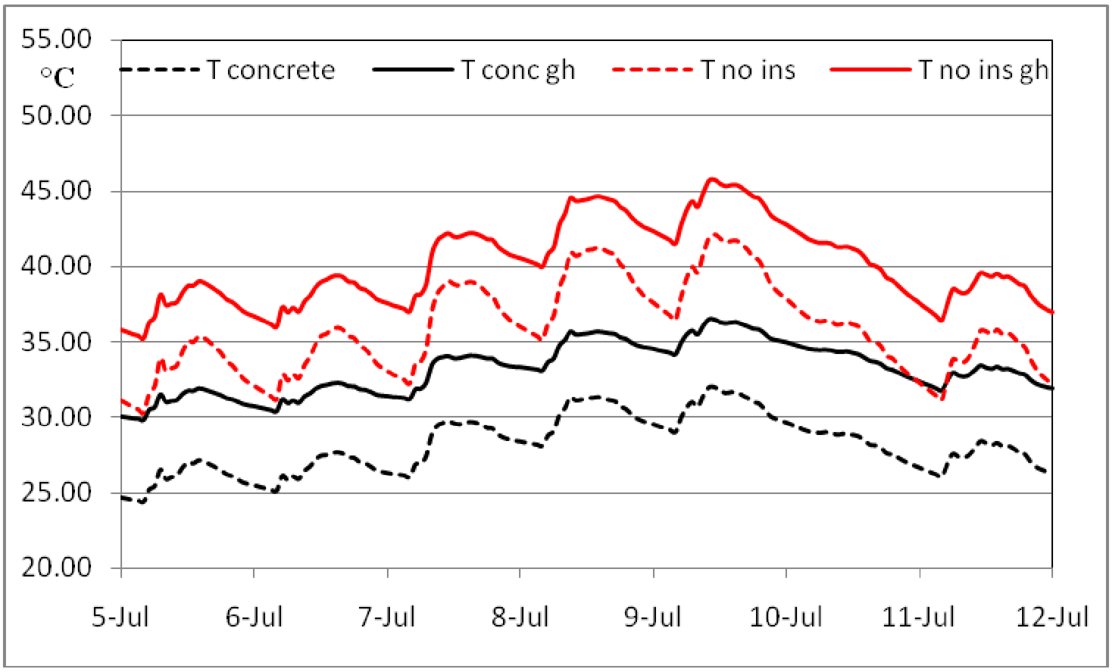
T light gh
T ref
T ref gh
T heavy gh

b)



c)

Figure 10.5 a)The difference in temperature for the different building types when they are place in the greenhouse or not. (T_{gh}-T_{ref}). b) Temperatures for the buildings with equal U-value with and without surrounding greenhouse. c) Temperatures for the buildings with higher U-values with and without surrounding greenhouse.

Figure 10.5 a) shows that the original building is the building least affected by the greenhouse and the lightweight the most affected.

In b) and c) as well as in Figure 10.1 and 10.2 it can be seen that the indoor temperature as well as the effect of the greenhouse is dependent on the design type rather than the U-value. The buildings' walls react differently to the changed temperature due to the greenhouse and to the reduction of solar radiation. The reason for this is explained in the next chapter, but here it can be said that the lightweight design reacts very distinctly to the solar radiation and the reduction of it through the greenhouse's walls. The original and heavier structures' reactions are much smaller, b). Also in c) the reactions to the reduced solar radiation are seen in the lower peaks but here, as previously discussed, the increase in surrounding temperature is the dominating effect on the indoor temperature.

10.4 Summary/Conclusions of chapter 10

The erected building is the warmest which makes it the most energy efficient when it comes to heating but it can also be very warm during summer (if not enough ventilation is used). It is also the building type for which the placement in the greenhouse has almost no effect on temperature and therefore also not on heating demand. All the buildings with U-value equal to the original building get cooled almost throughout the whole year by the greenhouse due to the reduction of solar energy through the greenhouse glass. This effect is most pronunciated for the lightweight structure. The greenhouse heats the buildings with higher U-values but this is not enough to compensate for the transmission losses.

11 Thermal effects of different wall constructions

This chapter contains an explanation of why the energy consumption differs for the buildings with equal U-value. In steady state calculations they would give the same result according to equation 10.1 above. It also explains the different shapes of the temperature curves for the different buildings. Below an extract of Table 10.2 is shown.

Table 11.1 Energy consumption for heating different designs with equal U-value

	Ref	**Heavy**	**Light**
Building [kWh/m^2,year] (kWh/year)	 87.9 (5535)	 87.1 (5490)	 90.6 (5710)
Building in greenhouse [kWh/m^2,year] (kWh/year)	 88.6 (5579)	 111.3 (7011)	 96.8 (6096)

11.1 Heat flux on the inside of the walls for an outdoor temperature rise of one degree

Figure 11.1 shows the heat flux on the inside of the wall when the temperature on the outside is suddenly increased with one degree (from 0°C to 1°C). After the rise the outside temperature is kept at one degree for the rest of the time period. Examined is the effect this outdoor rise has on the temperature on the inside of the wall. The indoor temperature is kept constant at 0°C. The flux on the inside is calculated as

$$q_{in} = (T_{s,in} - T_{in})\alpha_{in} \qquad (11.1)$$

with $T_{in} = 0$

$$q_{in} = T_{s,in}\alpha_{in} \qquad (11.2)$$

showing that the flow on the inside will increase as the inside temperature increases.

The temperature on the inside of the wall is dependent on the heat storage capacity of the wall, which in its turn is dependent on the materials and the order in which they are arranged. The heat storage capacity of a material is the same as its ability to absorb heat and this is dependent on the density, the thermal conductivity and the specific heat capacity of the material. This gives that even if the same amount of heat is given to the walls different amounts of it will be stored in the different walls. The larger the heat storage capacity of the wall the later the temperature change will be noticed on the inside of the wall. I.e. the wall with large heat storage capacity will appear to be less conductive.

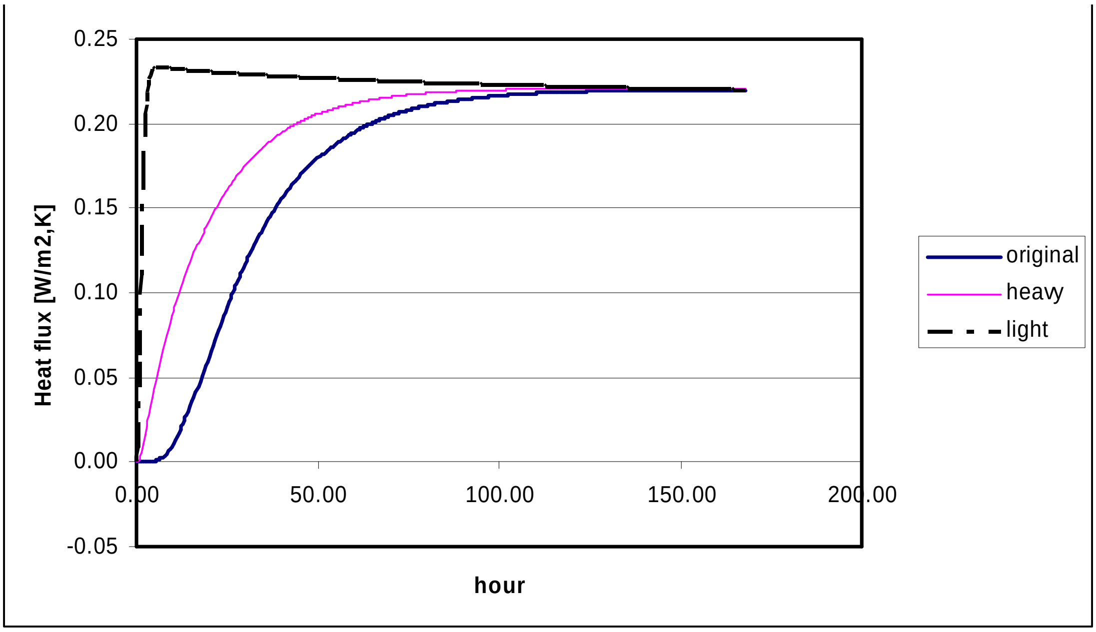


Figure 11.1 Thermal behavior of the three different wall constructions.

The flux on the inside of the lightweight wall rises very steeply in the beginning of the time period, due to low heat storage capacity, while the other walls have a more modest rise.

All the curves end at the same value, 0,22, which is the U-value for the walls. This shows that when the systems have become stable they will all have the same energy flow. But since the temperatures in reality very seldom stays constant these energy storage abilities will be in use almost all the time for the heavier walls, either absorbing or giving away heat, whilst the temperature on the inside of the lightweight wall will vary quickly with the outdoor temperature. Inside a building with lightweight walls a change in the outdoor temperature will be quickly noticed while it may hardly be noticed at all in a heavy building.

In Figure 11.1 is seems like the original wall has a heavier behavior than the traditional heavy wall even though it is made out of aerated concrete. This is due to the thickness of the wall. Changing it to correspond to the heavy wall through reducing the thickness of the aerated concrete layer to 100mm and adding 117mm insulation outside the concrete gives results as in Figure 11.2 below. Now the more intuitive result are obtained, with the heavy wall as the slowest to react.

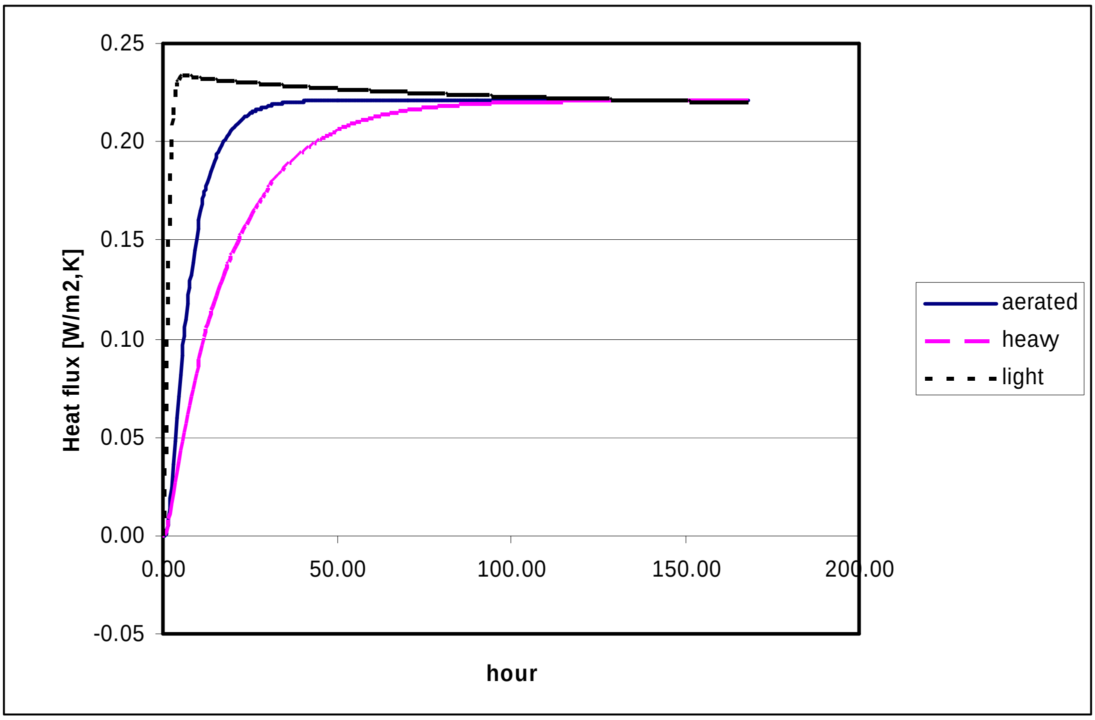


Figure 11.2 The thermal behavior of the walls when the thickness of the aerated concrete is reduced to 10cm and insulation is used to balance the U-value.

Thermal effects are also the explanation to the very different shapes of the temperature curves for the buildings, with the concrete building's flat curve and the lightweight designs steep changes, see for instance Figure 10.5 b) and c).

12 Results from LSA simulations and comparison of the results to the detailed model

The LSA model is a quick and simple model compared to the detailed one discussed above. If the results from the LSA model are close to those of the detailed model the LSA model can in many cases be used to give approximations of the energy demand and indoor temperature.

The LSA-model was originally constructed in the thought that the air in the greenhouse would function as insulation. Since this effect was negligible, see Chapter 9, the LSA is not especially suitable for buildings in greenhouses. Rather the opposite unless the model is developed to take into consideration the reduction of the solar radiation through the transmittance of the greenhouse's glass (which this one is not). There is a chance though that the building itself is enough insulated. Taking a quick look at the criteria for LSA in equation 12.1 and inserting V=151, A=108 and α=0.13 the result is that λ for the building must be smaller or equal to 1,82 and since the buildings maximum U-value is those for the glass parts of 1,7 the criteria can be considered fulfilled.(Hagentoft, 2001).

$$\frac{Lc}{d} \leq 0.2 \qquad (12.1)$$

$$Lc = 2\frac{V}{A}$$

$$d = \frac{\lambda}{\alpha}$$

Starting by looking at the energy used for heating in Table 12.1 below it can be seen that the LSA model overestimated the energy used for heating by 23%.

Table 12.1 Estimated energy consumption for the two models

	Energy consumption [kWh/m^2,year] (kWh/year)	Difference from detailed model [%]
LSA (With heat loads)	86.6 (6615)	+23
Building (With heat loads)	70.8 (4462)	/

The explanation for this is found in Table 12.2 and Figure 12.1 that show LSA-model underestimates the temperatures visibly compared to the detailed model.

Table 12.2 Monthly mean temperatures indoors for the models

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
T_{LSA}[°C]	3	4.9	9.4	20.1	28.8	32.3	35.2	31.6	25.5	18.2	10.8	5.2
T_{ref} [°C]	7.7	7	12.4	23.7	33.8	37.3	40.2	36.2	29.1	21.3	12.9	7.1

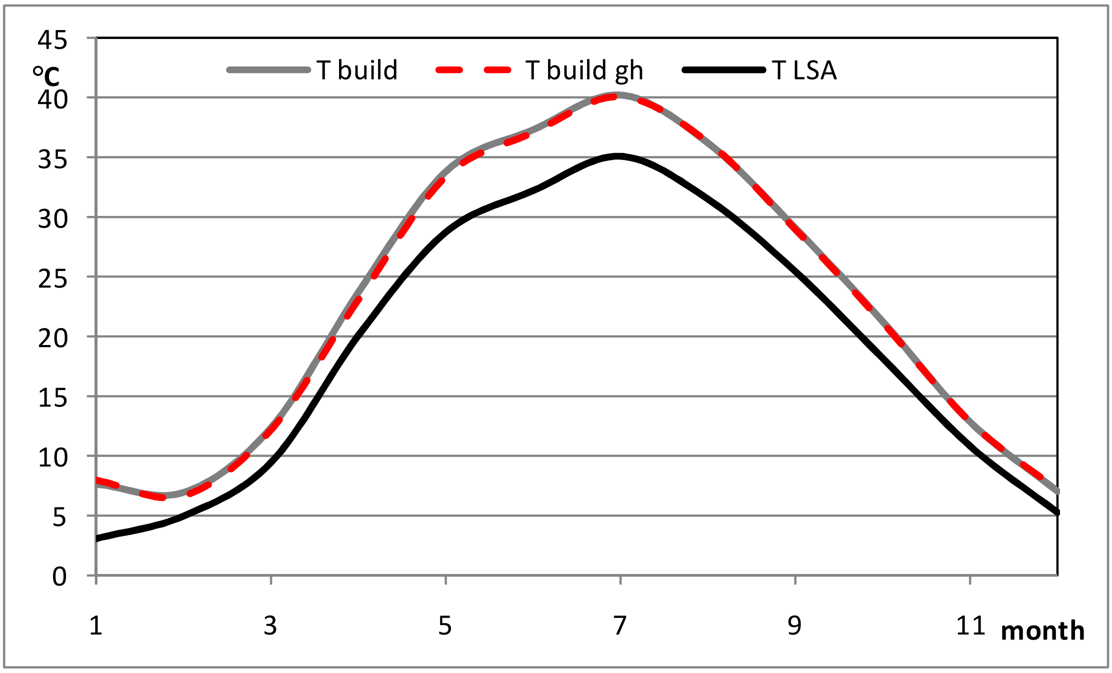


Figure 12.1 Monthly mean temperatures

13 Summary and conclusions

The main aims of this report are to present the climate in the greenhouse and the building and to examine the effects the greenhouse has on the climate in the building, both in terms of comfort and energy consumed for heating. Summing up the results as the answers to the questions posed in chapter 1.1, here divided into results/ conclusions for the greenhouse and results/conclusions for the building.

1. What will the climate in the greenhouse be and what parameters affect it?

Here there is a conflict between the measured and the simulated temperatures. The measured temperatures reach as much as 15°C above the outdoor temperature, during summer, while the difference for the simulated temperature never exceeds 3°C. None of the results are unfortunately very reliable; the measurements are made too close to the wall, due to placement problems, and the simulations are just simulations, with their inherent problems. The combination of the two assessments indicates that the temperature inside the greenhouse, especially in combination with ventilation, never gets unbearable. This is also in accordance with the owner’s opinion. During the winter the temperature in the greenhouse is close to the outdoor temperature, showing differences (warmer in the greenhouse) only for hours with intense solar radiation.

The temperature in the greenhouse is visibly affected by the ventilation rate and the size of the greenhouse (the temperature in general increases with the size). Sunscreens inside the greenhouse do not reduce the temperature since the glass and the frame is still allowed to be heated and a lot of the solar radiation is still allowed to enter the greenhouse. The orientation of the greenhouse is of small importance since the walls are made of glass.

The relative humidity does not appear to be a problem, the figures are rather insecure but the greenhouse is not used for growing so no additional water is added and the ground is covered with a layer of capillary breaking gravel.

For the greenhouse it would be beneficial to make new and better measurements of both temperature and RH.

2. What will the climate in the building be, how does the greenhouse affect the indoor climate and would another type of building design have been better?

Both the measurements and the simulations show that the temperature inside the building rises high during warm days (well above 30°C both for measurements and simulations). The building’s low U-value combined with its glass areas makes it easily affected by the intensity in the solar radiation. It also makes the orientations of the glass parts of the building important.

The sensitivity to solar energy causes the greenhouse to mainly have a cooling effect of the indoor temperature since the energy in the solar radiation is reduced through the greenhouse’s glass. For this type of building it is probably considered a positive effect during summer and a very slight disadvantage during winter. In order to have an energy saving effect of the placement in the greenhouse the U-value must be higher. But then the savings through the greenhouse’s warmer surrounding temperature is not enough to compensate for the buildings transmission losses compared to having a lower U-value. A lightweight design with U-values equal to the original is more affected by the solar radiation and surrounding temperature and hence also more affected by the greenhouse while a heavy design with U-values equal to the original is less affected by solar radiation and ambient temperature. The lightweight structure has a more comfortable indoor temperature during summer but needs about 10% more heating energy during winter than the reference building. The heavy structure has a smoother temperature curve but loses about 25% more energy than the reference building.

The relative humidity in the building is sometimes quite low but this is over all not a problem.

The Lumped System Analysis model is not suitable to buildings in greenhouses in the sense that the greenhouse would be insulating enough. For the reference building in this thesis the building itself is insulated enough for the LSA assumption to be valid. The LSA model underestimates the temperature in the building compared to the main model though leading to a deviation in estimated energy needed for heating of 23%.

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Drawings:

Drawings of the building were obtained from Unit Arkitektur AB.

Drawings of the greenhouse were obtained from Uno Borgstrand AB.

Photos:

All photos are taken by the author of this thesis.