INFLUENCE OF DIFFERENT BUILDING PRACTICES ON THE PERFORMANCE OF A PASSIVE SOLAR DESIGN GREENHOUSE

By

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To the faculty of Washington State University

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ABSTRACT

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The goal of the present paper was to study a greenhouse with a passive solar design (avoiding the use of extra heat supply but the Sun radiation) in order to determine if this greenhouse provided good growing conditions for vegetable during the Winter in a climate similar to the one observed in Eastern Washington, and which building practices or features represented the best option to achieve the goal of passive solar design.

The greenhouse studied presented characteristics similar to the one studied by Tong et al. (2009), but many of its constitutive parts were studied independently (glazing, slab design, building materials), such as the influence of several features like a covering blanket at night or fish tanks used as thermal mass. The experiments were based on comparing the results of a computer-aided simulation, using the DOE Energy Plus energy analysis software.

The general conclusions were that passive solar greenhouse can properly grow vegetables in the required conditions. More specifically, experiments showed that polycarbonates were the most suitable material for glazing in terms of energy efficiency; they highlighted the use of high thermal mass material as construction material, and proved adding water tanks to the greenhouse as thermal mass was a beneficial practice, such as adding a covering blanket at night. The best shape among those tested was a straight South facing roof with a 45° angle with horizontal.

The experiences also highlighted relationships between average air temperature, minimal air temperature, and standard deviation of the average air temperature on the one hand, and R-value of the slab and width of concrete on the other hand. The kind of relationship unifying these parameters is a logarithmic relationship for the average air temperature and the R-value, and a linear relationship for minimal air temperature, average standard deviation and concrete thickness. The best configuration for slab was the concrete at the innermost layer and insulation at the outermost layer.

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CHAPTER I. INTRODUCTION

Background and justification

Global warming due to anthropogenic emissions of greenhouse gases has provoked significant discussions worldwide. Model results from the Intergovernmental Panel on Climate Change (IPCC, 2007) show many negative consequences of climate change for society including increases in the surface temperature. To prevent the unfavorable effects of climate change, major efforts have been directed toward limiting greenhouse gas emissions. Greenhouse growers use large amount of fossil fuel to heat their greenhouse, which produces emissions and contributes a significant proportion of the operating costs: it can represent more than 30% of the overall operating costs of the greenhouse (Coffin, 1995). Thus, improving the energy balance of the greenhouse is an ecological but an economical choice as well.

This applies not only for greenhouses: energy savings is and is very likely to remain one of the priority for all the building construction and management for the years to come. Indeed, a recent survey by the National Association for Home Builders (New Home in 2015) revealed that in the next years the average home will be smaller and include energy saving/green features, with respectively 74% and 68% of respondents rating it as very probable broad trend over the next five years, far from the next point (more technology feature: 29%).

With these concerns in mind, passive solar design appears to be one simple and efficient way to achieve a good energy balance. Passive solar greenhouses are able to offer good growing conditions (significant amounts of light and temperature above the freezing point) with no or little additional heating needed, in order to provide fresh vegetables during the winter and starts

for the growing season. They represent a sustainable and efficient alternative to classical greenhouse. They are in accordance with sustainable development, as defined by the Brundtland Report of the United Nations: “sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Our common future, 1987). Indeed, they match the three bottom lines of sustainable development:

- Economic: passive solar design aims at lowering the heating costs without a major rise of costs, since it is only based on energy efficient building practices.
- Environmental: the reduction of fossil fuel consumption for heating purposes reduces the ecological footprint of greenhouses. Producing fresh vegetables in winter decrease the need of importing them from milder climate, and thus the fossil fuel consumption inherent in long distance good transportation.
- Social: an efficient greenhouse design enable year-round production, providing fresh and local vegetables even in winter, authorizing a healthier diet.

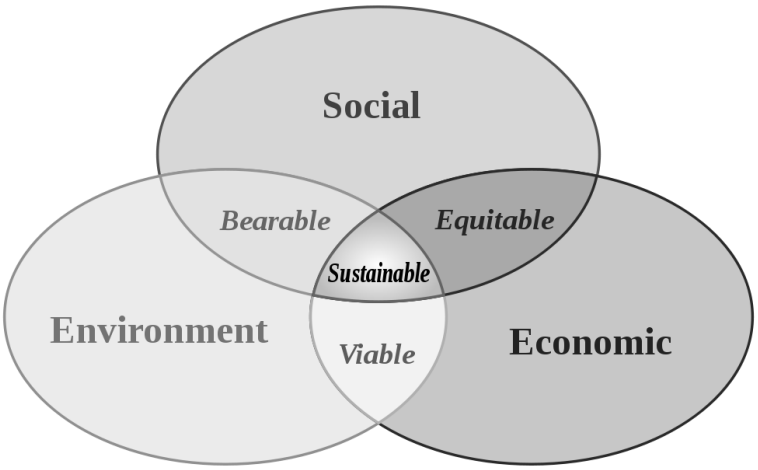


Figure 1: The three bottom lines of sustainable development (Adams, 2006)

Previous research

In the end of the 1980s, energy efficiency was a major concern since heating the greenhouse due to the large proportion of the operating costs. Garzoli (1988) emphasized measures that minimize energy requirements, such as minimized surface area, maximized solar radiation penetration, thermal mass and heat conserving covering materials.

Critten and Bailey (2002) have shown that greenhouse focusing studies made significant progress during the 1990s, and especially thermal and light transmission studies; computer modeling using finite elements techniques were used to improve resolutions of details. The authors emphasized the importance of light transmission and thermal properties of a greenhouse, and the need for an increased resolution in these studies.

Passive solar design greenhouses already proved to significantly reduce the energy needs when operating a greenhouse. Santamouris et al (1994) monitored a passive solar agricultural greenhouse for 2 years. The results showed that the passive solar design had energy needs equal to 35% of a conventional greenhouse. The main features of the greenhouse studied were high mass on north wall and a earth-to-air heat exchanger. These features focused on the thermal mass effect, storing and later releasing the heat gained in a warm period.

Chinese-style greenhouses have already been modeled in the past by Tong et al. (2009) through a computational fluid dynamics analysis. The authors compared their results with experimentally measured temperature during the winter and the simulated air and soil temperatures had the same profile. The study highlighted the fluctuation in air temperature and in humidity between daytime and night time. It showed too that the greenhouse was able to maintain a reasonable temperature even though the outside temperature was below freezing. The thermal mass effect of soil and

north wall was also highlighted, showing that the heat absorbed during the daylight hours was released when the temperature decreased and with no more solar radiations to heat the greenhouse. The covering blanket (a insulating covering deployed on the greenhouse) added when the solar gains were low appeared to prevent a lot of energy losses through the glazing, and this idea was studied in the present paper as well since it represents a good energy saving practice for greenhouses.

The relationship between thermal mass and insulation, which is a key parameter to obtain and maintain a good temperature in the greenhouse whatever the outside meteorological conditions are, were studied many times, as for example by Kossecka and Kosny (2001). The authors studied the heating and cooling loads in a building depending on different wall configuration (insulation inside or outside, varying thermal mass, etc.) and found that the best situation was insulation outside and thermal mass inside.

Study objectives

The objectives of this study are to evaluate the influence of different building parameters on the performance of a greenhouse with a passive solar design, in order to determine the most effective building practices to achieve energy neutrality. The study focused on the winter months between October and March, since it represents the most challenging period of the year for greenhouse growers, and is located in Pullman, WA, in the North West region of the United States. The summer months weren't addressed in that study, and the heat management issues related to that period still have to be considered for a proper greenhouse design.

Different simulations were performed to determine if the greenhouse could offer good growing conditions (temperature above freezing point at all times, with a desired temperature of 80°F/26°C).

Since thermal mass and insulation play a key role in any building energy performance, a quantitative analysis of these two parameters was performed in order to determine their influence on the greenhouse behavior.

The greenhouse was also designed to include aquaponics, since the large fish tanks involved in this technique could be used as thermal mass, and preventing the use of large amount of concrete or other building material. This was part of the wall study. A description of what is aquaponics is presented in Annex.

In the first chapter of this paper, the following portions of the design were investigated:

- Glazing of the greenhouse
    - Type: polyethylene film, polycarbonate, glass in different thickness

    - Shape: rounded, 30° slope, 45° slope
- Covering blanket
    - Influence of a covering blanket
    - Location of the covering blanket
- Adding fish tanks as thermal mass
- Materials: concrete, concrete masonry units (CMU), brick, autoclaved aerated concrete (AAC), plywood

The second part of this paper focused on the study of thermal mass and insulation, studying separately the slab and the North facing wall:

- Thermal mass and insulation
    - Slab: Thickness for a constant R-value,in 3 different configuration
    - Wall:Thickness for a constant R-value, 3 different configuration

CHAPTER II. COMPARATIVE STUDY OF PASSIVE SOLAR GREENHOUSE DESIGN

Abstract

The goal of this paper is to study a greenhouse with a passive solar design (avoiding the use of extra heat supply but the Sun radiations) to determine if this greenhouse provided good growing conditions in terms of temperature for vegetable during the Winter in a climate similar to the one observed in Eastern Washington, and which building practices or features represented the best option to achieve the goal of passive solar design.

The greenhouse studied presented characteristics similar to the one studied by Tong et al. (2009), but many of its constitutive parts were studied independently (glazing, slab design, building materials), such as the influence of several features like a covering blanket at night or fish tanks used as thermal mass. The experiments were based on comparing the results of a computer-aided simulation, using the DOE Energy Plus energy analysis software.

The study concluded that passive solar greenhouse can properly grow vegetables in the specified conditions. More specifically, experiments showed that polycarbonates were the most suitable material for glazing in terms of energy efficiency; they highlighted the use of high thermal mass material as construction material, and indicated that adding water tanks to the greenhouse as thermal mass was a beneficial practice, such as adding a covering blanket at night. The best shape among those tested was a straight South facing roof with a 45° angle.

Introduction

More than 30% of the overall operating cost of a greenhouse are spent on heating (Coffin 1995). Moreover, CO_2 is usually emitted from the heating system, because common greenhouse heating systems rely on fossil fuel consumption (butane, electric from non renewable sources, etc). A sustainable approach for greenhouse grower would be to move toward reducing energy consumption reduction. This would reduce the ecological footprint and by the way the energy bill of the greenhouses.

A way to achieve this goal would be to apply passive solar design to greenhouses. The heating requirement would be reduced or even eliminated, such that all the energy needed would be satisfied by solar radiations. The greenhouse would also have to establish a safe and healthy environment for plant growth. Each plant has its own minimum, maximum and optimum temperature (Wielgolaski, 1966), hence a key parameter for greenhouse management is air temperature. In this paper attention was given to average air temperature because it is related to growth speed (Myeni et al, 1997)(Went, 1953), minimum air temperature since freezing or cold temperature can cause huge damage to the plant (Burke et al, 1976) and standard deviation of the average air temperature, as it is related to plants stress from the variation of temperature (Myeni et al, 1997)(Went, 1953).

Previous work has been done on reducing the energy need of a greenhouse: Garzoli (1988) recommended to reduce the surface or employing thermal mass. Santamouris et al (1994) proved after a 2 year monitoring, that passive solar design could reduce the energy need by 65% compared to a standard greenhouse. The energy saving strategy for this greenhouse was oriented on energy storage, with a lot of thermal mass on the north facing side and an air to ground heat

exchanger. Arinze et al (1984) and Thomas and Crawford (2001) used water tanks as a thermal storage with successful results.

Tong et al (2009) applied several techniques such as rounded south facing glazed surface, North facing wall was highly insulated and with a large thermal mass, or the use of a covering blanket at night with convincing results in terms of growing conditions.

All these different experiments prove that passive solar design can be achieve by simple design practices such as South facing orientation with a non glazed North wall with increased thermal mass and insulation, energy storage devices like water tanks, covering blanket, etc.

But to maximize the efficiency of the building, these principles have to be adapted to local conditions, and the special requirements of the building usage. Greenhouses have very specific needs, and are a real challenge to adapt to the passive norms: they require a lot of sun exposure, consistent temperature above freezing point, ventilation.

Thus, designing a passive solar greenhouse requires specific and adapted building practices. The overall objective is to improve the growing conditions of the plants. This paper focuses primarily on the temperature and energy flows in a greenhouse; it aimed at maximizing the temperature related conditions in the greenhouse. To do so, a general approach would be to maximize the solar gains and minimize the heat losses to balance the equation:

$$\text{Energy balance} = \sum heat\ gains - \sum energy\ losses$$

Since the goal is to achieve passive solar design, the only authorized heat gains are solar gains, provided by radiations from the sun. This energy is transferred to the air and in anything located inside the greenhouse, and to the greenhouse itself, especially the thermal mass (slab, wall, etc.)

The energy losses are all the energy transferred from inside the greenhouse to outside. The primary losses are through the glazing, then losses due to external air infiltration are secondary and finally the heat losses through ground floor, walls and roof.

Hence each part of the greenhouse has to be designed carefully to select the most efficient configuration possible. The greenhouse components tested in this study were the glazing material and shape, the wall material, the effect and the best location of a covering blanket, and finally the modification of the greenhouse behavior when adding thermal mass via fish tanks such as the one used in aquaponics.

The glazing was studied thoroughly because it is a major source of heat losses, as it was observed during a modeling presented later in this study. The wall materials were tested too, since they are a source of heat loss as well.

The covering blanket (a insulating covering deployed over the greenhouse at night) is a device that appears to be efficient (Tong et al, 2009), and it was included in this paper to study its potential.

Since aquaponics is an agricultural technique gaining interest for use in greenhouses (see appendix), the influence of the fish tanks required for this method were measured.

Methods

Overall approach

In order to determine the building practices that would maximize the energy balance, a building performance software - Design Builder - was used. Energy analysis programs (Energy Plus, Design Builder, Ecotect) are a very powerful tool to determine the environment conditions and the energy flows of the building, and understand how the greenhouse perfoms under specific building conditions and climate.

In order to design a passive solar greenhouse as efficient as possible, each component was tested and optimized. To do so, the study was based on a baseline design greenhouse, whose component were separately modified and tested in order to optimize the configuration. For each option of each component, performances were compared to the baseline to see if they really carry a relevant optimization. The timesteps for calculation was set on an hourly basis.

Decision was made to start from an already existing passive design, the Chinese-style greenhouse presented in (Tong et al, 2009) adapted to common practices in North America. See below for an extended description of the baseline greenhouse and the greenhouse rationales.

Building performance and design software

Why a building performance software

Building performance software gives the result of a whole year exposure to climate within a few hours, whereas actually building the greenhouse and measuring the environmental conditions with sensors or other devices would require significant time and money. In addition, using simulation software eliminates calibration errors or uncommon weather conditions, since the weather data used are typically averaged over ten years, which provide the most accurate prediction of how will the greenhouse behave on a typical year or winter.

Modeling the greenhouse behavior gives the opportunity to modify and improve the design many times, and consider many different options for building practices (covering blanket, various thermal mass amount, etc.) It enables accurate trends and determines the optimum configuration of the greenhouse.

The software chosen to do so is Design Builder, because it is a graphic engine for Energy Plus, which is the US DOE building energy simulation program for modeling energy flows (including air conditioning, solar gains, etc.) It is one of the industry standards; one of the reasons is that it provides accurate results due to reliable weather files (see next paragraph for more information). However, Energy Plus requires coding skills, whereas Design Builder allows creating a design directly in the software, from extrusion from floor plan for example. Even if it is getting more popular, Ecotect wasn’t picked because it does not use Energy Plus for the modeling calculations.

The weather files

The behavior of the greenhouse depends heavily on its outside environment; that's why climate is a key point for a good modeling. Depending on the climate input for the software, the results obtained can vary a lot, and accurate weather files are necessary, to prevent the "Garbage In – Garbage Out" phenomenon (bad data as an input for the software would result as a meaningless output after simulation).

The weather files are usually hourly datasets, available in many formats; one of the most popular one is Typical Meteorological Year (TMY3) from the U.S. National Renewable Energy Laboratory (NREL) in the 1990s. It consists in annual average of weather variables calculated over a the 1991-2005 period. The data are presented hourly and represents a typical year for the period.

Energy Plus uses modified weather data files (format .EPW, standing for Energy Plus Weather), shorter and including sub-hourly fractionation. More information are available on (Crawley et al, 1999).

Method validation

In order to prove that building performance software is a suitable tool for greenhouse behavior analysis, the same greenhouse as the one presented in Tong et al (2009) was modeled and its performance under the same climatic conditions were predicted by Design Builder.

The greenhouse is a passive solar agricultural greenhouse corresponding to a common design in North China according to Tong et al (2009), that is employed to produce fresh vegetables year-round and especially in the winter, which can be very cold (the average temperature in Shenyang for the month of January is -11°C). The main notable features are a north wall combining thermal mass by the use of bricks and a high level of insulation, a south facing orientation and the use of a blanket covering partially or totally the glazed part, depending on the Sun exposure.

The greenhouse was modeled to the specifications in Tong et al (2009, and weather data corresponding to the described meteorological conditions were created in order to be an input for the building performance software. Tong et al (2009) mentioned in their paper the external climatic conditions they measured for the four days the experiment lasted. The described parameters were the air temperature outside, the total solar radiation outside on a horizontal surface and the air humidity outside. However, these parameters didn't include all the parameters that can be found in a weather data file (for example data about the wind or the dew point). In order to use the best weather data file as possible, it was decided to use the weather data file that was the closest from the greenhouse: the weather data file emitted by the Shenyang airport in China, and modifed according to the data presented by Tong et al. (2009).

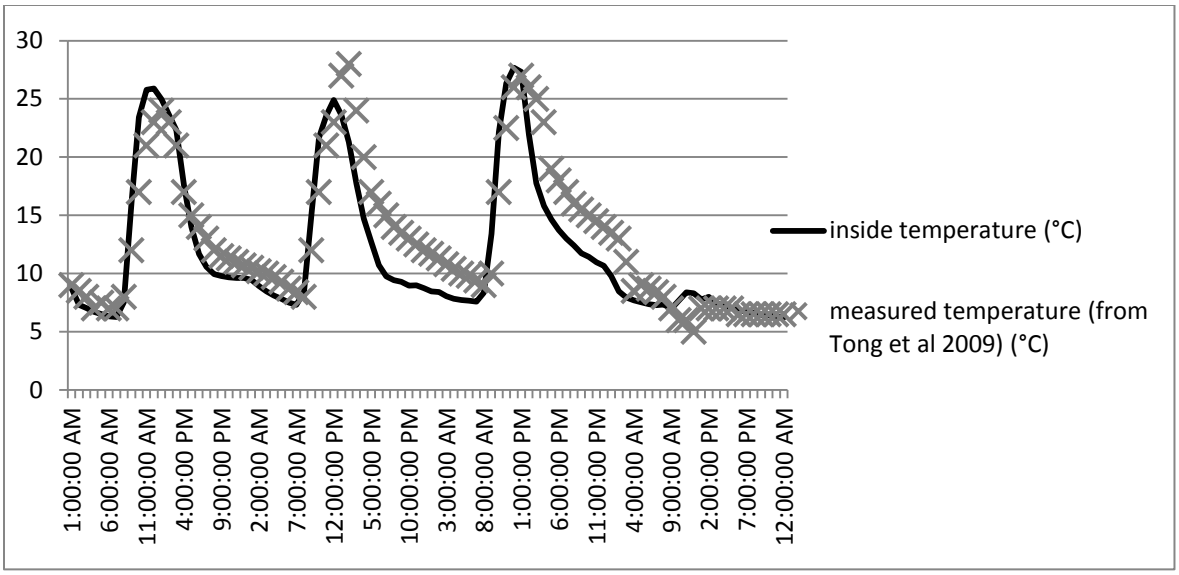


Figure 2: comparison of simulated (black line) and measured (grey dots) temperature variations inside the greenhouse for 4 days - measurements from (Tong et al, 2009)

Results obtained by the simulation were very close to the ones measured by Tong et al (2009): the mean squared error of the average temperature difference between simulated and measured temperature over four days is 2.82°C. The mean squared error is particularly low on the first and fourth day (respectively 2.30°C and 1.74°C), whereas on the second and third day it is equal to 3.04°C and 3.11°C. The minimum temperature difference recorded was 0.01°C and the maximum 7.24°C, showing that the simulation was very close to the measurements of Ton et al (2009). The differences might come from the fact that the input weather files were created based on the weather data proposed by Design Builder, which correspond to the .epw format averaged data describer earlier, updated with the environment data available in Tong et al. (2009). The data available were air temperature, solar radiation and relative humidity; this doesn't include wind speed/direction or dew point, which can explain the differences on second and third day. Another explanation would be there could be some imprecision in the model, especially concerning air tightness or other hard to measure parameters that weren't described by Tong et al (2009).

The general trend is for the software to predict temperature that are a bit lower than the measured ones, and a temperature rising in the morning faster that what is observed in reality. Hence it can be said that the model is generally conservative, since it actually predicts worse conditions than what really happens, except for a few moments such as the morning temperature rise.

It was concluded that Design Builder performance simulation is a reliable tool to predict and model the greenhouse behavior under given weather conditions.

Description of the greenhouse – baseline design

Design Rationales

The greenhouse used as a baseline greenhouse was based on a passive solar design greenhouse presented in Tong et al. (2009), in order to use the benefits of this experience. The shape and the materials selected for the baseline design are inspired by the Chinese style greenhouse studied in the previously mentioned article, and are adapted to meet common building practices for greenhouse in Northern America and durability criteria. The design of the greenhouse was also adapted to enable aquaponics culture in the greenhouse.

Overall design description

The greenhouse was chosen to be located in Pullman, Eastern Washington, USA. It was south facing to maximize sun gains. Dimensions were 18.29m (60 ft) in length by 9.14m (30ft), corresponding to a medium sized greenhouse. These dimensions were picked in order for the greenhouse to be able to host three to four aquaponics units, based on S&S Aquafarm design (see in annex for more details). One unit includes one fish tanks and 6 growing beds.

The North wall was set at 2.44m (8ft) to enable ease of movement in the greenhouse. The North roof was sloped with a 45° angle with horizontal. This was to correspond with the solar elevation at noon on 31 March in Pullman, WA. Hence it combines minimal slope and maximized direct sun rays penetration in the greenhouse for the winter period, since 45° is the highest Sun position in the sky for the period of interest (See Fig. 3). A lower angle would have the roof blocking the sun rays at noon, which is not desirable since maximal sun gains are required, and a higher angle would increase the volume of the greenhouse and thus the volume of air to renew and heat, leading to a waste of energy.

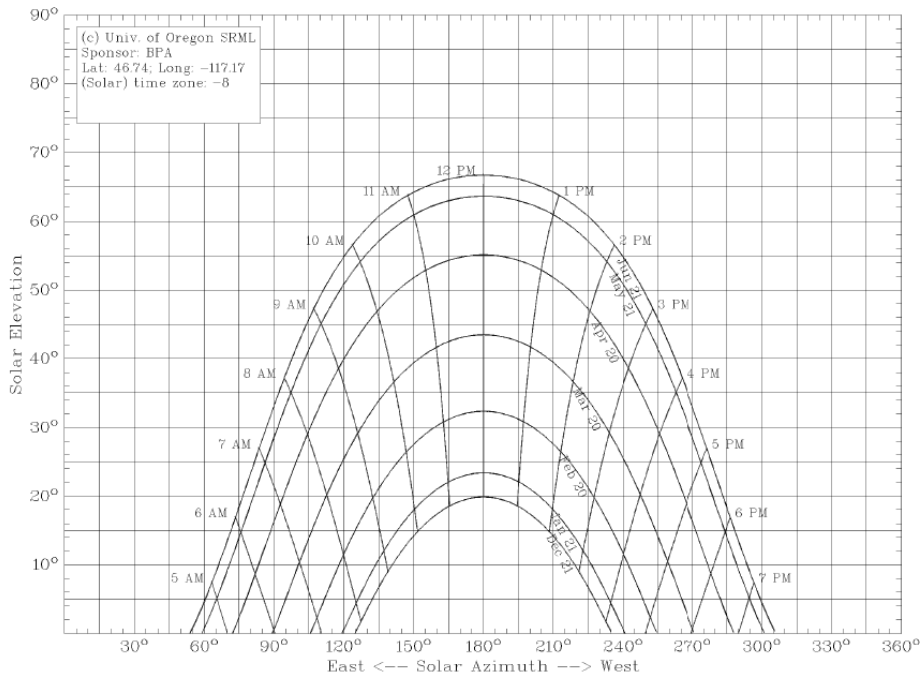


Figure 3. -Solar elevation in Pullman, Washington, USA. Credit to University of Oregon Solar Radiation Monitoring Laboratory

The South roof consisted of two parts:

- a 1.10m (3.6ft) straight roof with a 45° angle with horizontal. This specific feature was designed to put solar heat panels (a solar collector that is designed to collect heat by absorbing sunlight) on the additional surface exposed to the sun. These are not present in the current study, but they could be in future research on the greenhouse in order to provide additional sun gains, or be used as a source of energy for heating the fish tanks that require a temperature between 27°C and 16°C (80°F to 60°F). This is still considered passive solar gains.

- a glazed rounded surface. The round design was chosen based on practical consideration: the majority of greenhouses sold in the United States have a tunnel or “half-pipe” shape. Choosing a shape similar to this design would help the greenhouse farmers who want to put the passive solar design proposed in this study into practice to find commercial products that would fit their need.

This is a choice made by the authors, and needed to be evaluated. This study appears later in this paper. The south half of the greenhouse is exactly the same as a half tunnel-shaped commercial greenhouse, and the side walls of the greenhouse (East and West wall) are 50% glazed. The fact that the side walls are 50% glazed differs from what was employed by Tong et al (2009), and it represents an assumption that wasn't studied thoroughly in this paper.

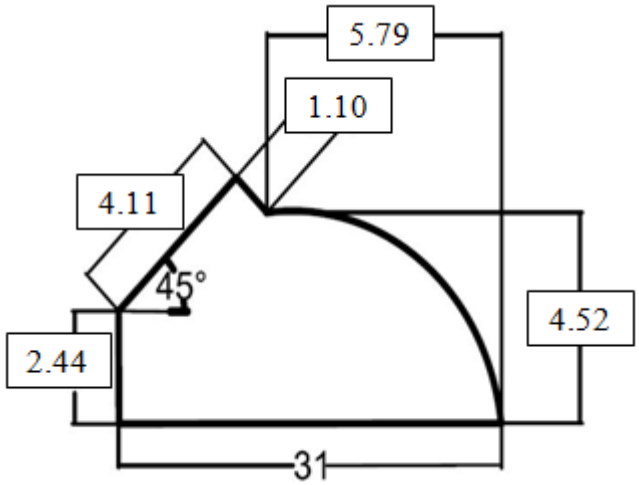


Figure 4.- Side view of the greenhouse design. Dimensions in meters

Design details and justification

The insulating material thickness has been adjusted for the greenhouse to have a consistant R-value for all surfaces but the glazing, according to the passivhaus recommendation for energy efficient houses. The target value was set around R-5 m^2K/W (R-30 ft^2-F-h/Btu), based on what was observed in (Tong et al, 2009).

Since sustainability is based on long term vision, materials were chosen in order to provide the greenhouse a minimal 10 years lifetime, especially concerning the glazing. This was to prevent generating a lot of waste made while renewing components of the greenhouse, glazing for example.

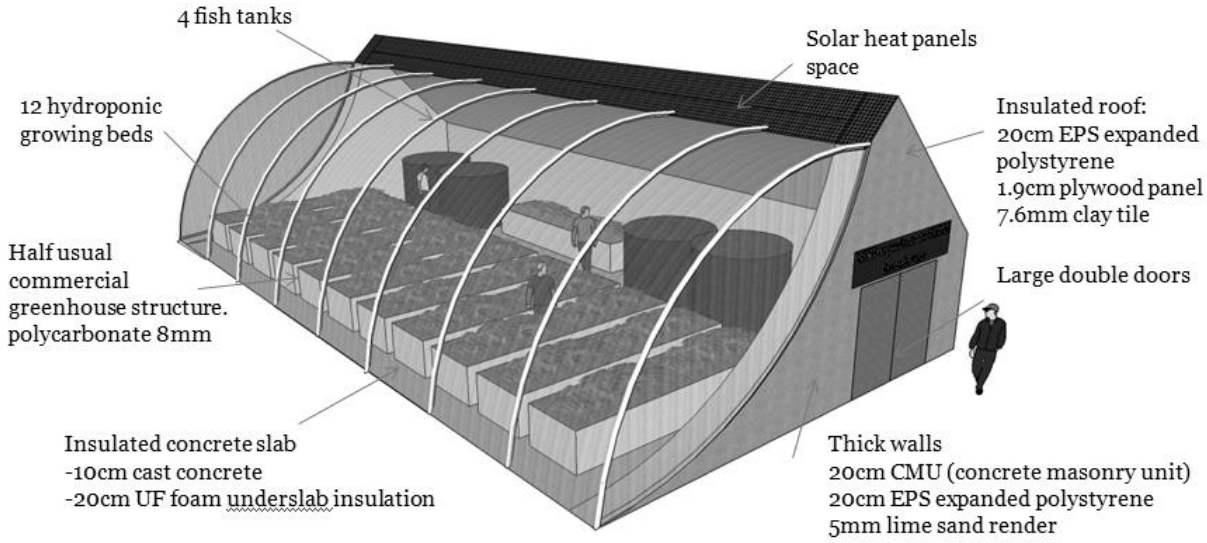


Figure 5. description of the baseline greenhouse, with the aquaponics system included

The following characteristics and materials were chosen:

- ***Glazing :*** 8mm polycarbonate twin wall on the rounded side (R-value=0.47 m^2K/W = 2.680 ft^2-F-h/Btu), and on the East/West wall side.

  This material represents common practice for greenhouses that are not using polyethylene films. Indeed, PE films have a 4-years lifetime, whereas polycarbonates have a minimal 10-years lifetime.

- ***Slab****:* 10cm (4") of cast concrete with 20cm (8") UF foam underslab insulation (R-value=5.32 m^2K/W = 30.357 ft^2-F-h/Btu)

  Structural calculations for sizing the concrete thickness necessary were not performed for this study, because these calculations depends on the concrete type, the soil type, and the building construction rules of the place where the greenhouse would be built.

  The insulation thickness was adjusted to fit the target value mentioned earlier. It was

chosen to put the insulation underslab according to the recommendation usually made in terms of insulation location, and to the one presented by Kossecka and Kosny (2002).

- ***Walls:*** 20cm (8”) CMU (Concrete Masonry Unit) +20cm (8”) EPS expanded polystyrene outer insulation + 5mm (0.2”) lime sand render (total R-value=5.63 m^2K/W =32.130 ft^2-F-h/Btu)

  CMU is a cheap construction material that has a large thermal mass, which is a key factor for walls and slab according to (Tong et al, 2009). 8” is one of the standard widths proposed by the industry for this construction material in the United States.

- ***North roof:*** 20cm (8”) EPS expanded polystyrene and 1.9cm (24/32”) plywood panel +7.6mm (0.3”) clay tile (total R-value=5.33 m^2K/W =30.424 ft^2-F-h/Btu)

  Plywood is a common construction material, and it is what has been used by (Tong et al, 2009). Clay tiles are there to protect the insulating material from rain and other weather hazards. They have little or no influence on the energetic performance of the greenhouse since they have small thermal mass and insulating properties .They were preferred to other covering materials like asphalt shingles or rolled asphalt that are cheaper but with a three to five years lifetime.

Performance analysis

The previously described greenhouse was modeled in Design Builder and its performances for a typical winter (October to March) in Pullman, WA were analyzed.

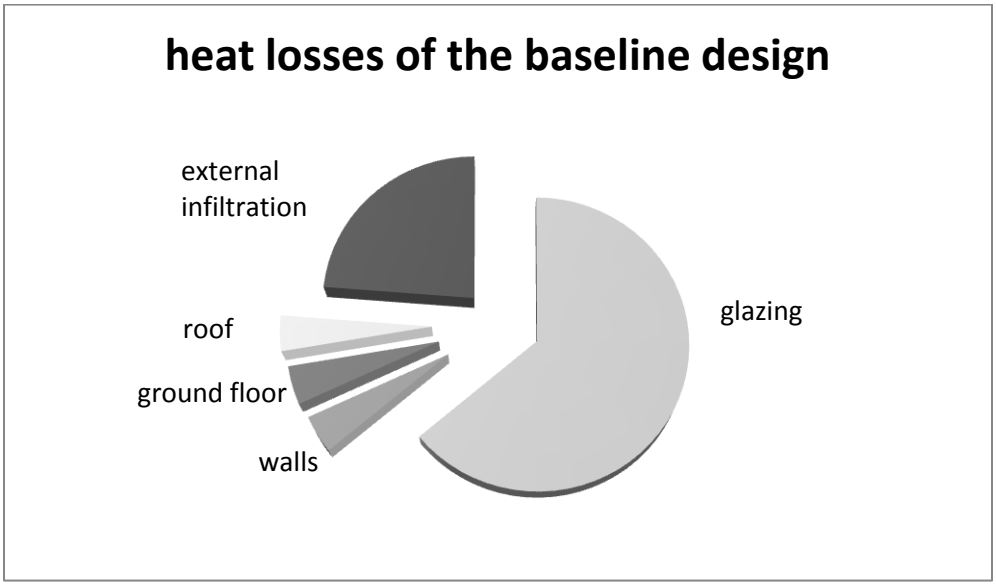


Figure 6.- Pie chart of the energy losses simulated in the greenhouse for a whole winter

The main source of heat loss of the baseline design is the glazing; it is a major point to study to increase the energy efficiency of the greenhouse. This is likely to be the result of poor R-value of the glazing compared to the rest of the greenhouse, and the fact that IR (Infra Red) radiations are not blocked, which means that a lot of energy is lost through radiant energy transfer. Thus, the conduction and radiation are the prominent ways of heat losses for the greenhouse. The simulation didn't provide any information relative to the origin or location of the heat loss, hence the impact of other factors like wind blowing on the greenhouse or rain wasn't explicitly measured.

The external infiltration is a parameter of the simulation that can be set; it represents the air infiltration that naturally occurs in a building. It is not suitable to decrease it, since for a

greenhouse air renewal is important. It highlights the importance that should be given to the ventilation system, preferring energy efficient ventilation system like double flow AC or any system minimizing the heat loss occurring by air exchange. Solutions that could be implemented for that greenhouse in terms of air exchange efficiency are presented in Annex.

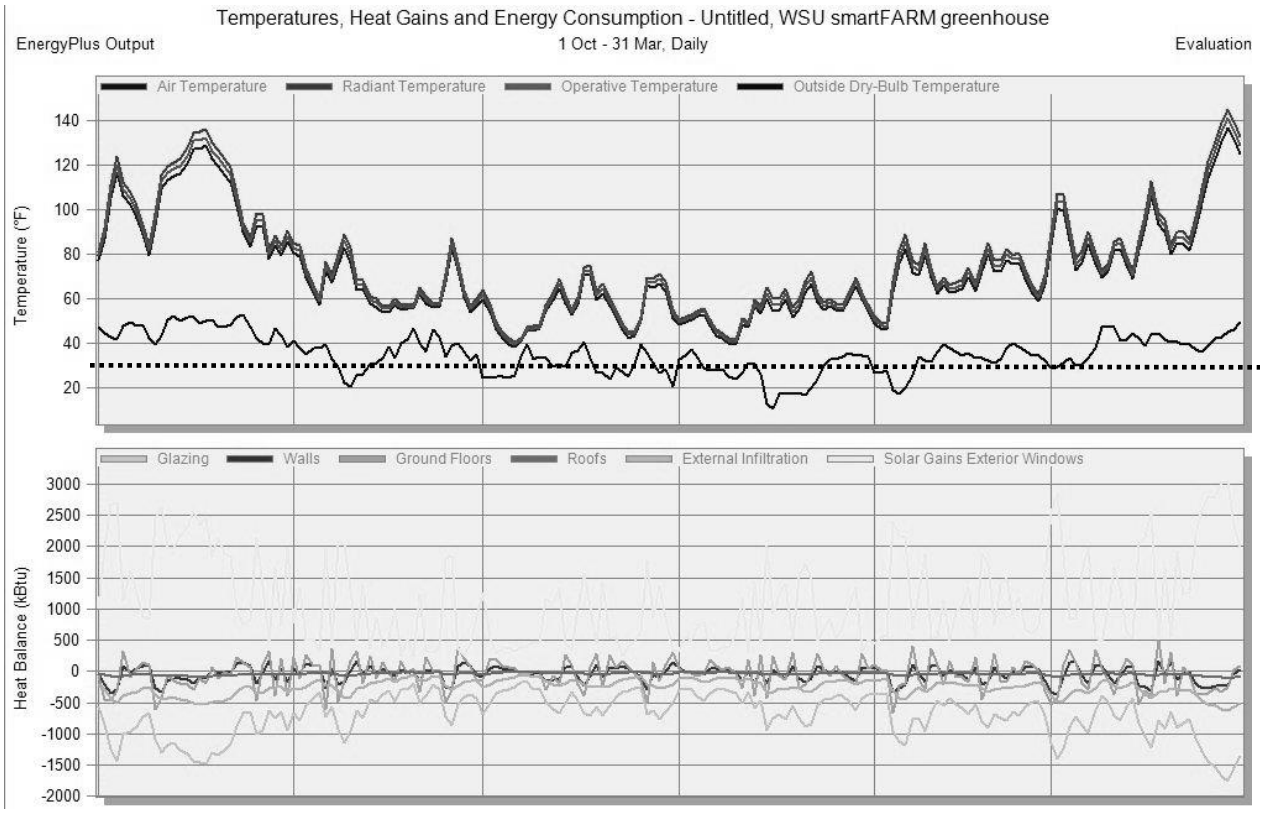


Figure 7.- Results of the simulation for temperature and heat balance of the greenhouse through the winter in Pullman, WA, USA

The baseline design enable a year round growing period in terms of temperature, since the air temperature inside must never go below freezing point (dot line at 0°C = 32°F). Temperature control features have not been set, that is why sometimes temperature is too high (over 30°C = 86°F), but if such temperature can be reached it means that they can be easily reduced by simply opening the windows, since the outside air temperature is always at that time below 10°C =

50°F. The challenge for a greenhouse in winter is more to maintain high temperature than controlling overheating.

The thermal mass effect of walls and ground floor is visible on this graph, because on days of lower light and hence lower solar energy input, the walls or ground floor don’t act anymore as a heat sink but a heat source: the energy balance for these two particular components (light brown and purple lines) becomes positive. This can especially be observed when the sun gains are reduced.

Experimental design

Glazing study

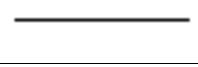
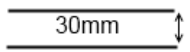
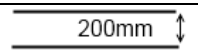
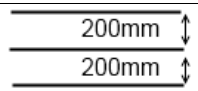
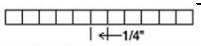
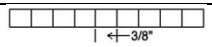
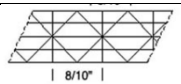
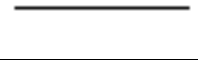
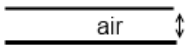
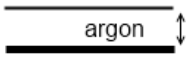
Glazing material

In order to compare the efficiency of different common glazing material, a set of 13 simulations were performed. The first one was the baseline design tested for a complete winter (1st October to 31st March), with each successive test represents a model with a different glazing.

Materials tested are described in Table 1. They correspond to the major glazing materials employed for greenhouse glazing, and some combinations (like triple layer PE films) are not used for the moment, they are tested in order to know if they represent an interesting alternative.

The R-values presented in Table 1 were calculated by Design Builder, accordingly to the input specifications found on manufacturers' website or in the Design Builder material database.

Table 1: Materials tested for the glazing study

Material	**Type**	**picture**	**Light transmission**	**Calculated R-factor (ft^2-F-h/Btu-in)**	**Expected lifetime (years)**	**Comments**
Polyethylene film	PE single layer		85%	n/a	4	Easy to install, inexpensive, short lifetime
	PE double layer 30mm air gap		72%	2.29	4	Easy to install, inexpensive, short lifetime, need inflater
	PE double layer 200mm air gap		72%	2.29	4	
	PE triple layer 2x30mm air gap		61%	3.58	4	Easy to install, inexpensive, short lifetime, need inflater This system does not exist yet at large scale. I was tested in order to see if it could be beneficial in terms of energy balance
	PE triple layer 2x200mm air gap		61%	3.57	4	
Polycarbonate	6mm twin wall		88%	6.77	10	Cheap material, long lifetime. 25mm wall can't be bent. Easy to install.
	8mm twin wall		87%	5.40	10	
	16mm triple wall		79%	3.81	10	
	25mm six wall		63%	3.76	10	
Glass	3mm single layer		90%	0.9	25	High cost material. Scratch resistant. very long lifetime
	Double layer 3mm/6mm air filled		82%	1.82	25	
	Double layer 3mm/13mm argon		65%	3.03	25	

Shape of glazing

Three different glazing shapes were tried: the baseline design, a 30° slope straight south roof and a 45° slope straight south roof. They all had the same materials and features (see baseline design), only the shape was changed. See Figure 8 for the details of the different plans. The footprint of the different greenhouses obtained was the same, and they all had a 45° north roof and a space for solar heat panels as presented in the baseline design greenhouse. A 1.22m (4feet) vertical glazed surface at the front of the glazed surface was added in order to maximize the useful space in the greenhouse, since it enabled to have planters or growing beds as far as possible.

The different greenhouses were modeled and tested under the same climate conditions from October to March. The performances of each greenhouse where compared in order to determine the most efficient design, based on the parameters of average air temperature, standard deviation of air temperature average and minimal air temperature.

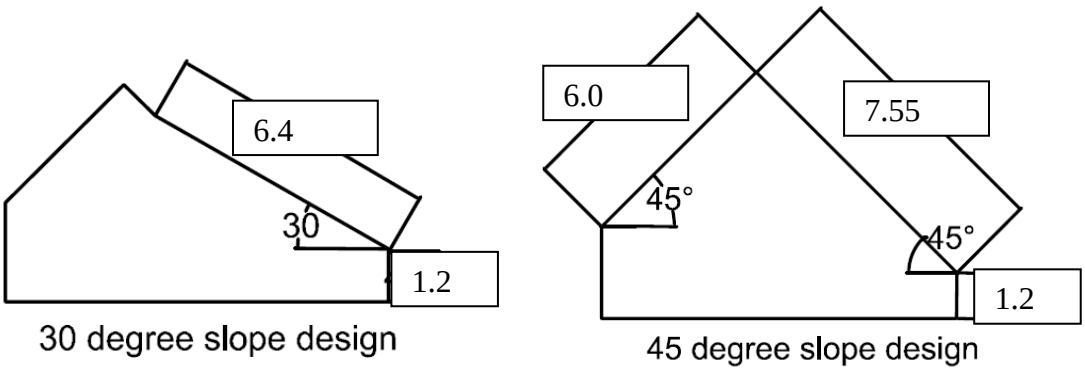


Figure 8. side views of the two other designs studied in the shape study, with dimensions that are different from baseline design. Dimensions in m

These different designs have different side areas (see Table 2), and hence the three different greenhouses have different volumes. The 30° slope greenhouse has a slightly lower volume than the baseline one, and the 45° has a larger volume (+15%).

Table 2. Side area of the three tested designs

side area	Area in sf		Area in m^2		% compare to baseline
round	369.98	sf	34.4	m2	
30°	352.735	sf	32.8	m2	-4.66%
45°	422.73	sf	39.3	m2	14.26%

The other shapes tested were closer from what is usually observed for greenhouse. The literature discusses mostly straight roofed greenhouse: Tomas and Crawford (2001) used a south roof with a 45° angle, and Bellows (2003) recommended a 45° to 60° for northern latitude in the US, and 20° to 40° for milder climates.

Covering blanket study

Adding a covering blanket

The same experimental protocol as the experiment studying thermal mass and insulation of the slab presented in (Pirou, 2011) was performed, with a new parameter: adding an insulating blanket at night. The conditions controlling the blanket use were:

- inside air temperature below 18.3°C = 65°F (to prevent greenhouse overheating)
- night time

The results for each slab were compared to the results of the equivalent simulation with no blanket performed during the slab study of (Pirou 2011).

Table 3. Specifications of the covering blanket

parameter	value
Thickness (m)	0.0254
Conductivity ($W.m^{-1}.K^{-1}$)	0.043
Solar transmittance	0.00
Solar reflectance	0.90
Visible transmittance	0.00
Visible reflectance	0.90
Long-wave emissivity	0.50
Long-wave transmittance	0.00

Location of the covering blanket

The method employed was to compare the result of a non covered and covered greenhouse with different locations for the blanket (inside or outside). The blanket employed was the one previously employed for the blanket experiment (See Table 3). It was deployed if it was night and with a temperature below 18.3°C = 65°F (to prevent greenhouse overheating). The results of the simulations were compared one to each other based on different parameters: energy losses, average and minimal air temperature, and standard deviation of the average air temperature.

Adding thermal mass inside the greenhouse

The goal of this experiment is to study the effect on the building behavior if three 1.57m (5’2”) high x 2.29m (7’6”) diameter fish tank are added to it. The growing beds are not modeled for this experiment because the growing medium (vermiculite, clay pellets, rock wool, etc.) was not chosen at that time, and therefore couldn’t be modeled properly.

The method employed for this experiment was similar to the other experimental setup presented in this paper: adding thermal mass to the building and compare the output data to the baseline design on the same parameters and conditions.

The software only accept 2 layers of 48.26cm (=19 inches) of water = 96.52cm (=38 inches) as a maximum, instead of 1.57m (5’2”) inches. The total exposed area simulated is

area= π*(7.5^2)/4*4tanks*62inches/38inches

$$\text{area} = \frac{\pi * 7.5^2}{4} * 3\text{tanks} * 62\text{inches}/38\text{inches} = 216\text{ft}^2 = 20.1\text{m}^2$$

Wall material

For the same wall configuration, different common building materials at different thicknesses were modeled on the baseline design, and then the results were compared to the baseline results.

The different materials tested were CMU, aerated concrete, brick, and wood. Thickness depended on common building practices with the material

- CMU (concrete masonry unit): 4” – 6” – 8” – 10” – 12” (respectively 10.16cm, 15.24cm, 20.32cm, 25.4, 30.48cm)
- AAC (autoclaved aerated concrete): 2” – 4” – 6” - 8” – 10” - 12” (respectively5.08cm,

10.16cm, 15.24cm, 20.32cm, 25.4, 30.48cm)

- brick: 4” – 8” – 12” ” (respectively 10.16cm, 20.32cm, 30.48cm)

- wood panels (plywood): 3/8” – ½” – 24/32” – 1” – 1.5” (respectively0.95cm, 1.27cm, 1.91cm, 2.54cm, 3.81cm)

Results and discussions

Glazing

Type of glazing

The results of this simulation pool are presented in Figures 8 and 9. Figure 8 is a bar chart representing the total energy balance for the twelve energy simulations that were performed. Each energy balance is the difference between the sun gains and all the heat loss sources taken into account by Design Builder: losses through glazing, floor, walls, roof, and external infiltration (heating the cold air entering the greenhouse). The improvement compared to the baseline material (6mm polycarbonate) was calculated as an improvement percentage:

$$\%_{improvement} = \frac{(material\ energy\ balance - baseline\ energy\ balance)}{baseline\ energy\ balance}$$

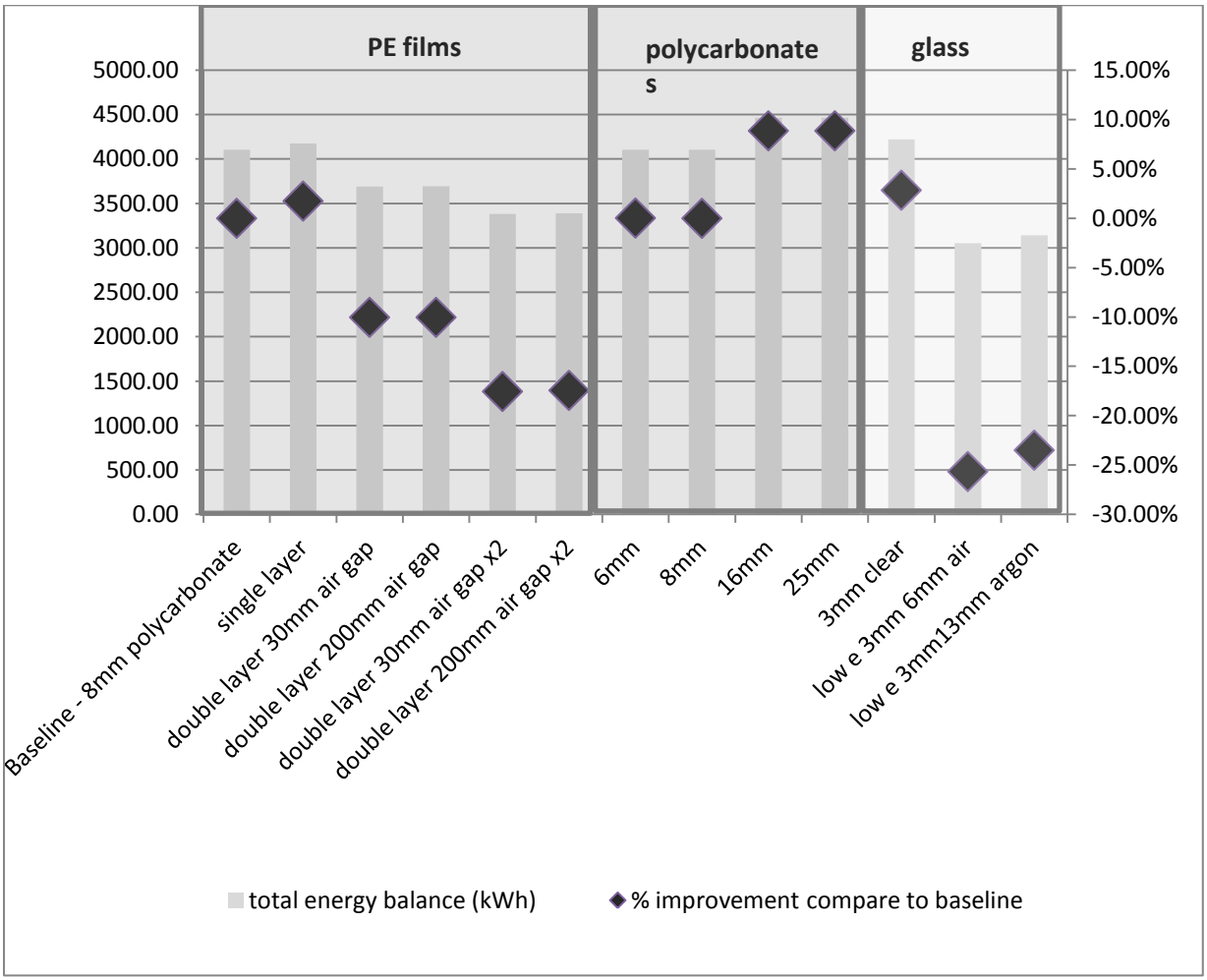


Figure 9. Total energy balance and relative improvement compare to the baseline of twelve greenhouse glazing materials for a typical winter

Figure 10 represents the average air temperature in the greenhouse for the whole winter and the error bars associated with each average. The error bars corresponds to the standard deviation associated with each average. Let:

N: number of temperature value (here 181 values, 1 per day)

t_i: temperature measured at time i (here I goes from 1 to 181)

t_a : average temperature for the set of data

$$\text{Standard deviation} = \sqrt{\frac{1}{N}\sum_{1}^{N}(ti - ta)^2}$$

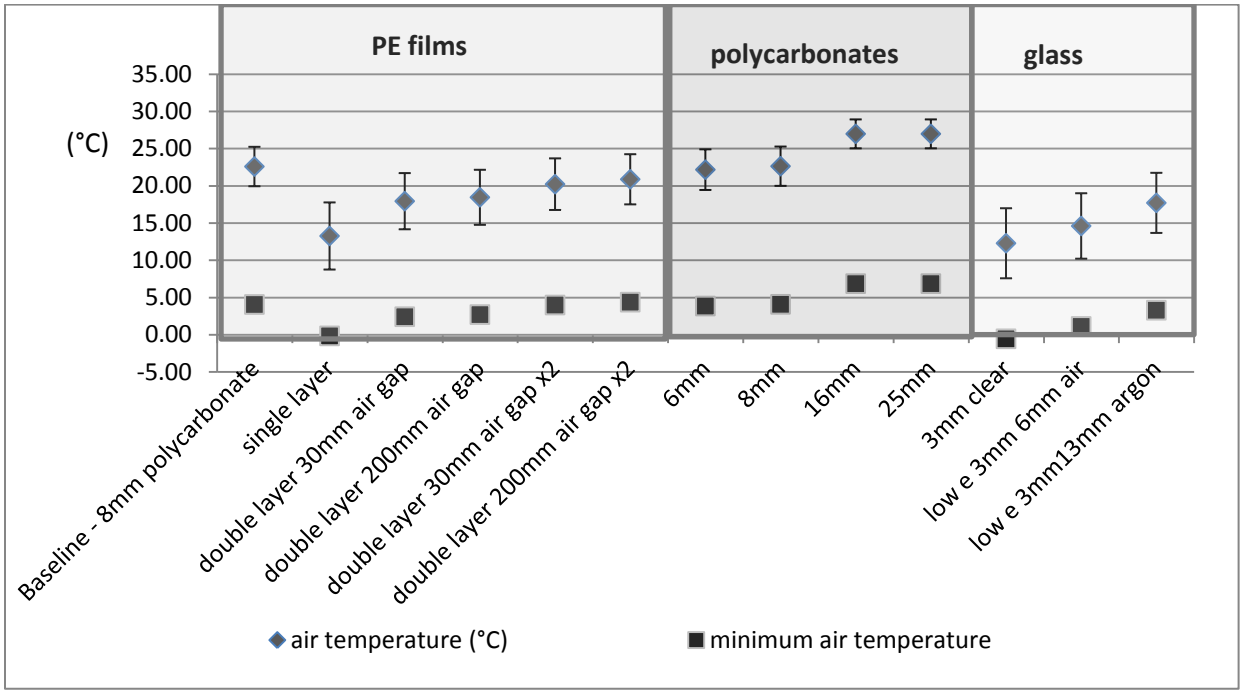


Figure 10. average air temperature and minimal air temperature in the greenhouse for twelve different greenhouse glazing materials for a typical winter

Discussion

A good glazing material has high solar gains and minimizes the losses through the glazing; hence it has a high energy balance. On equal energy balance, the best material is the one minimizing heat losses, because by the way the air temperature inside is higher. Average temperature and minimum air temperature are key parameters too, since one of the objectives of the greenhouse is to maintain the temperature above the freezing point. Thus, a good material has a high average temperature with a low standard deviation, and a minimal air temperature over 0°C (=32°F).

The best materials are the polycarbonates, which have the best energy balance and enable an average air temperature over 22°C (=72°F), without the temperature going below the freezing point. The good results for the PE film single layer or 3mm clear glass in Figure 8 has to be balanced with the fact that it has high energy losses, which explains the low average air temperature; in addition it is sometimes freezing in the greenhouse with these materials which is eliminatory.

The high average temperature does not represent a realistic simulation of what would happen in a real greenhouse: sometimes the temperature in the greenhouse reaches high values (over 38°C =100°F), temperature at which the greenhouse operator would already be cooling the greenhouse to prevent plants overheating, by opening the door/windows for example, the outside temperature being far lower than that. But in order to compare the materials on equal performances basis, choice was made not to implement overheating prevention measures.

A general conclusion was that a good glazing material has a high light transmission and R-value.

The complete results of this experiment can be found in appendix.

Shape of glazing

The goal of this experiment was to find a functional and energy efficient shape for the glazing. The baseline design is inspired by the work of Tong et al. (2009), and this experiment was designed to test if the rounded shape of the glazing presented in their article was the most efficient one compared to 30° and 45° straight south facing roof.

The complete results of this experiment are presented in Appendix. The parameters of average air temperature, standard deviation of air temperature average and minimal air temperature are presented in Figure 11.

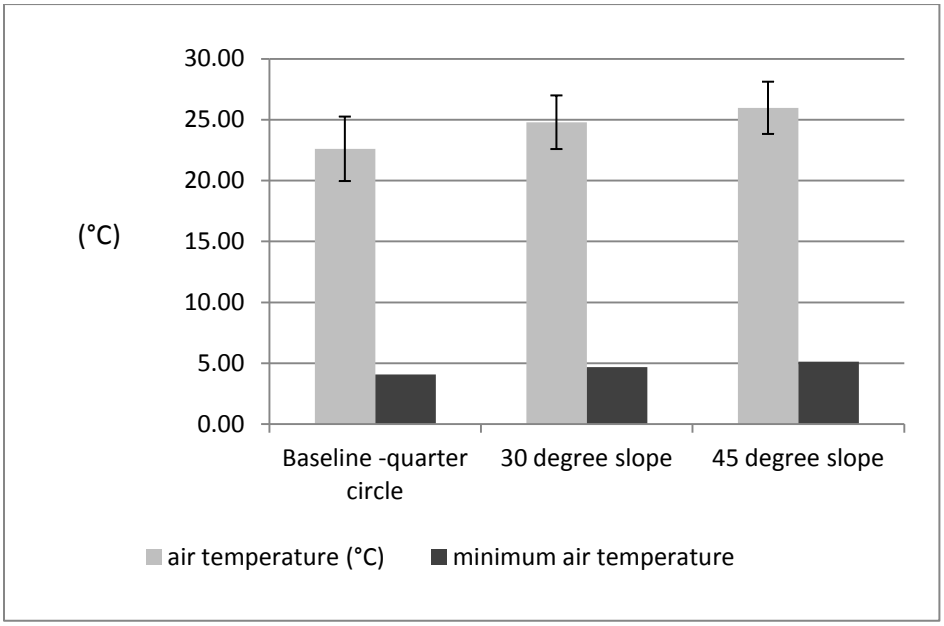


Figure 11. graph of the results of the shape study

Discussion

Comparing the different parameters, it appeared that the best design is the 45° slope design. Indeed, it proposed the highest average air temperature and minimal air temperature, and the lowest standard deviation among the different tested designs, even if it is the one with the largest volume of air inside the greenhouse. However, it is the one requiring the most

construction material, since it has the largest perimeter, which means that for an equal footprint, it is the most expensive greenhouse in terms of construction material.

The reasons why this design was more efficient because the Sun exposure of the greenhouse: since the sun is low during the winter (See Figure 3), a straight South roof with a high angle increases the incidence of the Sun rays on the glazed surface and reduces the part that might be reflected.

These results correlated the common “rule of thumb” that for the best results in solar design (http://www.builditsolar.com/SiteSurvey/site_survey.htm), the angle should be equal to:

Angle = (90 – latitude)

The latitude of Pullman being 46.73°N, the angle should be 43.27°, which is very close to the 45° slope which showed the best results.

Covering blanket study

Adding a covering blanket

Tong et al (2009) or Arinze et al (1984) highlighted the positive effect of covering the slanted front side of the greenhouse with an insulating blanket during the night or when the luminance is low. The blanket helps to maintain the heat inside.

The goal of this experiment was to study the effect of adding an insulating blanket at night on the greenhouse as presented as a good greenhouse management practice by (Tong et al, 2009) ; and study the effect of adding an IR blocking film on the greenhouse to prove the thermal mass effect of concrete. Indeed, if the concrete acts as a thermal mass it will catch heat from sun exposition during the daytime and release it by radiant heat (hence by IR radiation) during the night. Blocking the IR should reduce this effect.

The same experimental protocol as used in Pirou (2011) was followed, with increasing level of thermal mass and insulation for three different slab configuration, but with adding a covering blanket during the night. The results of both simulations were then compared.

Slab1: underslab insulation

All the relevant results for this experiment can be found in appendix.

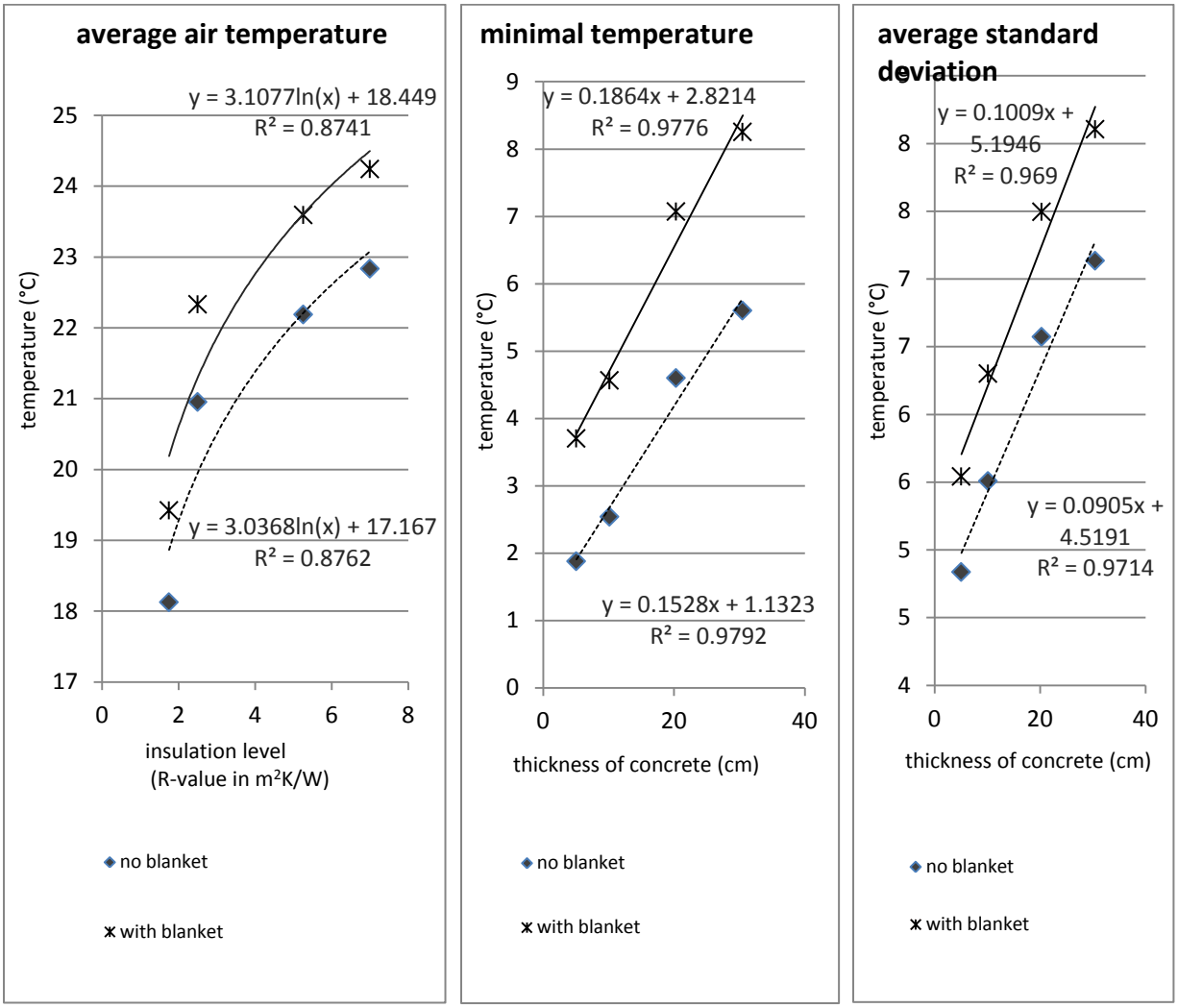


Figure 12. averaged results of covering blanket experiment for slab 1: average air temperature depending on R-value, minimal air temperature/standard deviation depending on concrete thickness - with or without blanket

All the relevant results for this experiment can be found in appendix

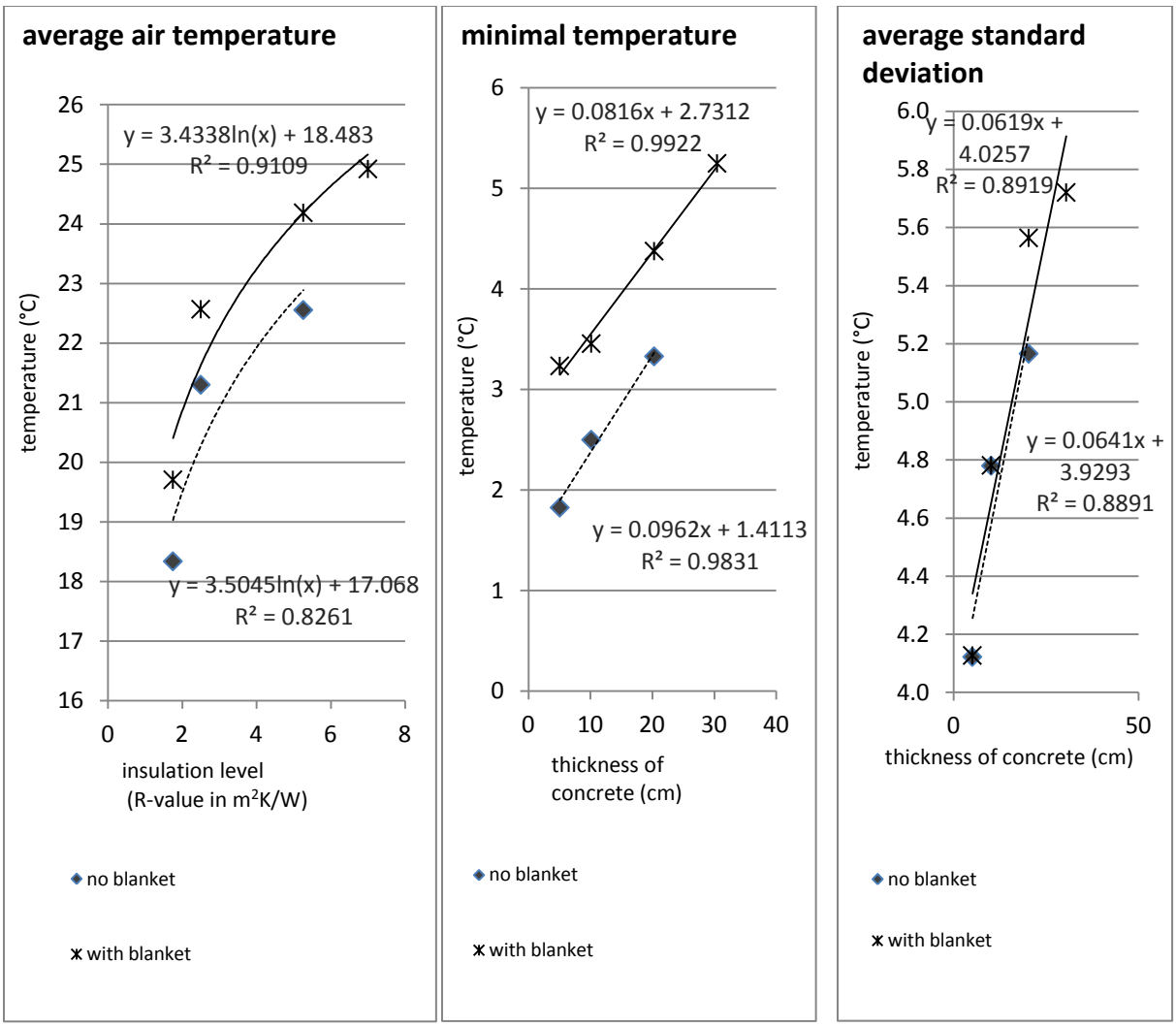


Figure 13. averaged results of covering blanket experiment for slab2: average air temperature depending on R-value, minimal air temperature/standard deviation depending on concrete thickness - with or without blanket

Slab3: sandwich insulation

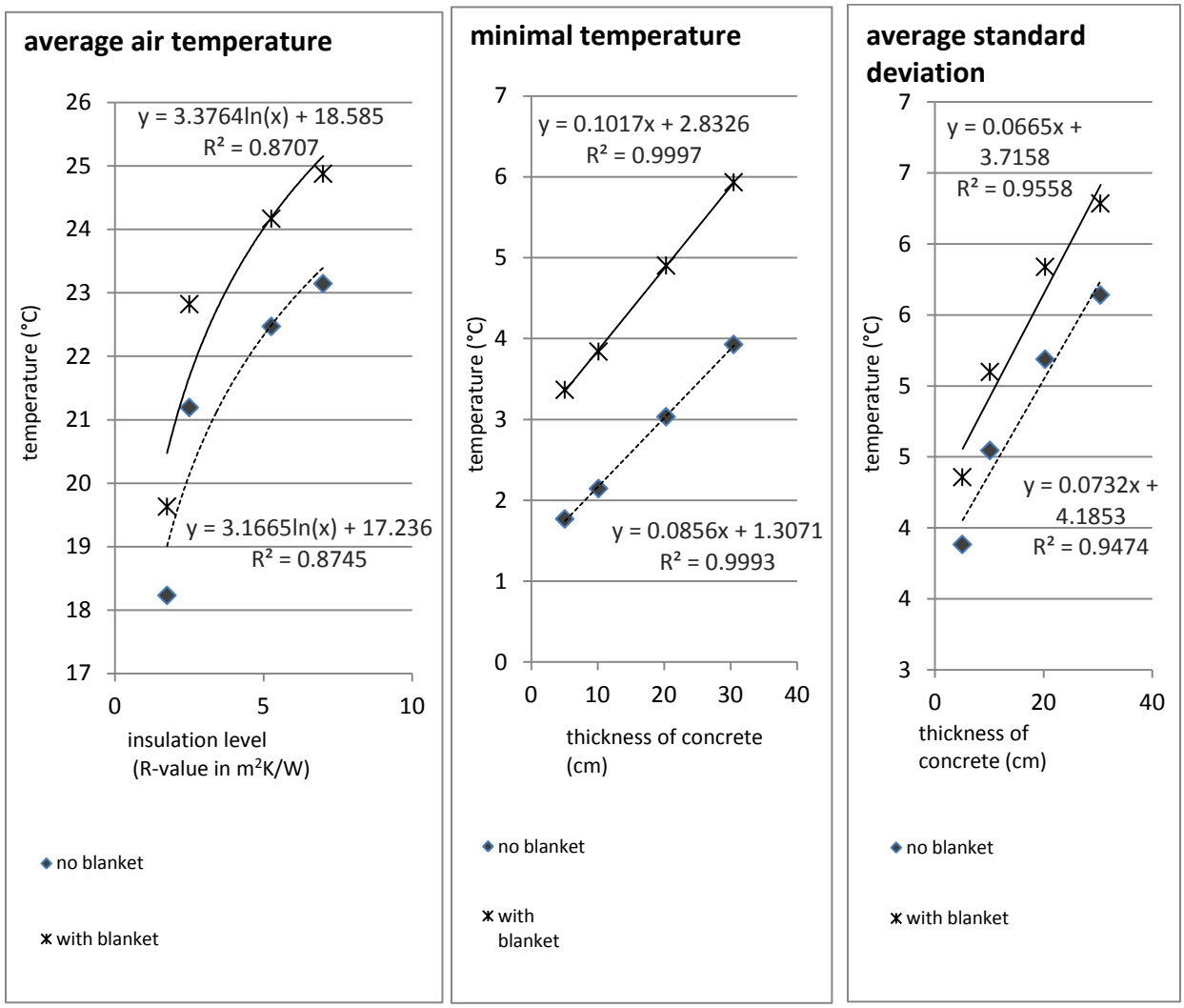


Figure 14. averaged results of covering blanket experiment for slab3: average air temperature depending on R-value, minimal air temperature/standard deviation depending on concrete thickness - with or without blanket

Discussion

Looking at the different graphs (Fig. 12, 13, 14), it appeared that adding an insulating blanket offsets the graphs' lines without modifying the slope significantly for average temperature graph and minimal temperature graph. Indeed, the Y-intercept of the different trend lines increases whereas the slope does not vary a lot, and the coefficient of correlation R^2 is always over 0.94.

Let A and B be the constant coefficients in the equation guiding the behavior of the average air temperature: average temperature = A*ln(R-value)+B or in the equation guiding the minimal air temperature : minimal air temperature = A*thickness of concrete + B. The average relative increase of coefficient A for the average air temperature was low with +3.64%, meanwhile the average relative increase for coefficient B was much larger: +7.6%. Concerning the minimal air temperature, A increased by 1.85% whereas B increased by 119.74%.

It means that the relationships studied in the slab experiments remain valid (logarithmic for the average air temperature/R-value couple, linear for the minimal air temperature and average standard deviation/thickness of concrete couples), and that the blanket increased uniformly the temperature with no influence of the insulation level or the thermal mass level of the greenhouse.

Adding a covering blanket leaded to the consequence of an increase of around 10% of losses through the ground can be observed, meaning that less concrete slab heat is lost via the other direction (the glazing) via radiant heat and hence it is the consequence of the IR blocking blanket.

As a general conclusion for this experiment, it appeared that using a covering blanket at night lead to valuable results in terms of greenhouse temperature management, confirming the

conclusions of Tong et al (2009). This practice showed that it has the potential to improve significantly both the average temperature inside the greenhouse and the minimal air temperature inside the greenhouse, and this independently from the insulation level or the thermal mass level of the greenhouse.

Location of covering blanket

Studying the influence of a covering blanket showed that this feature had a beneficial impact on the greenhouse behavior. However, the location of the covering blanket still needed to be studied. Indeed, such features exist in houses or similar small scale building (Window Quilt®, Silhouette blind, etc.), but they are usually located inside. This experiment aimed at comparing the performances of the greenhouse with a covering blanket inside and outside the greenhouse.

The complete results can be found in appendix. The most significant results are presented in Figure 15.

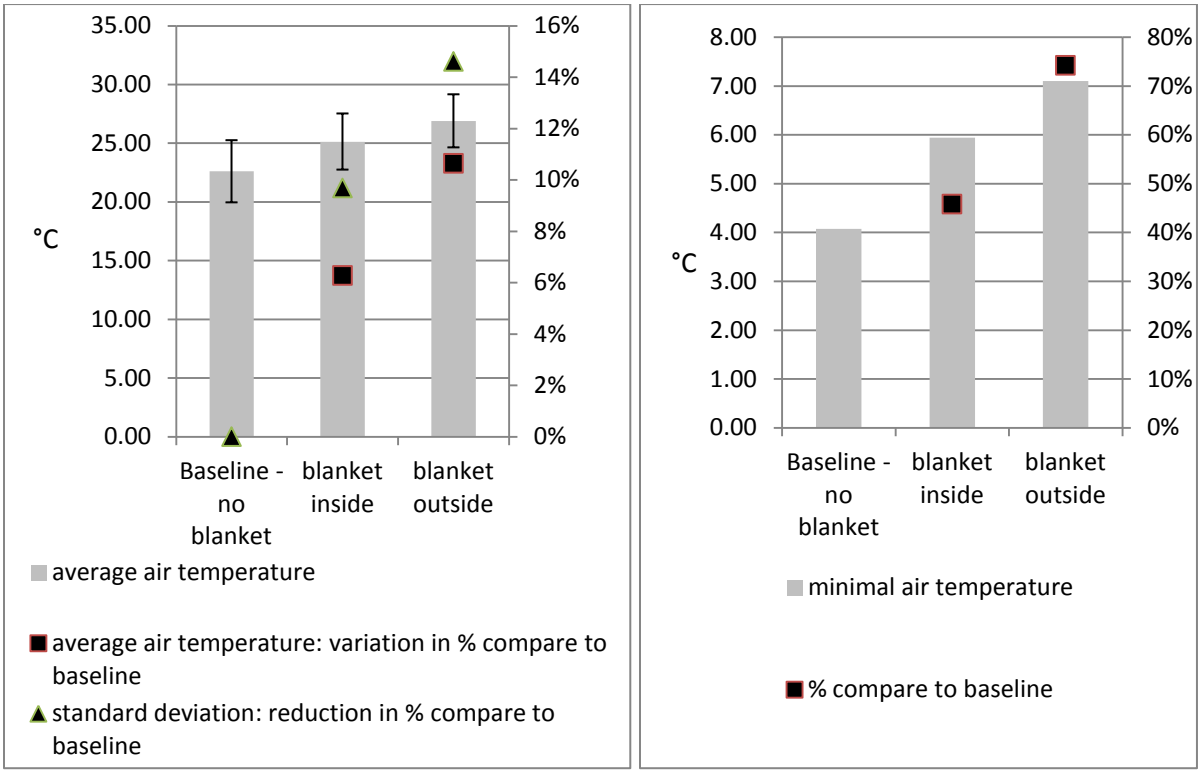


Figure 15. Comparison of the results of the greenhouse blanket location experiment, on the parameters of average air temperature, standard deviation of average air temperature and minimal air temperature

Discussion

Comparing the different results from this experiment, it appeared clearly that locating the blanket outside the greenhouse was the best configuration: the average air temperature was increased by

10.64% compared to a no-blanket configuration if the blanket was located outside (6.28% if inside), the minimal air temperature dropped by 74.22% from 4.08°C (45.80% if located inside) and the standard deviation was reduced by 14.61% (9.68% if located inside). All these results showed clearly that the best location for the blanket was outside, and that adding a blanket added a significant improvement to the greenhouse energetic behavior. The plants in the greenhouse would grow in a milder environment with a higher air temperature in average and with less temperature variations; and the coldest temperature they would have to face would be significantly increased, which would enable higher yields and to grow more plant species.

The reason why the blanket worked better while located outside could be the reduction of thermal bridges effect. Indeed, if the blanket is located inside, thermal bridges would likely appear at the junction between the glazing and the roof or the ground. However, this couldn't be proved with the simulations performed.

Adding thermal mass in the building

Arinze et al (1984) and Thomas and Crawford (2001) had positive results in utilizing water as a thermal storage in a greenhouse: indeed, the water collects energy during the daytime and release it during the night. The experiment presented here evaluated the influence of adding fish tanks that would be suitable for aquaponics in terms of energy efficiency.

Indeed, the greenhouse modeled in this paper was designed in order to be able to incorporate the agricultural technique of aquaponics, which is based on a combination of aquaculture and hydroponics growing. This technique is more extendedly described in Appendix. The design was largely influenced by the recommendation of S&S Aquafarm, with the objective of being able to host a maximum of four aquaponics units, composed of one fish tank and 6 growing beds each. This represents a maximum for the greenhouse; three aquaponics units represents a nominal configuration, since it makes it more convenient and practical in terms of space management.

Table 4.comparison of the results of adding thermal mass as fish tanks to the greenhouse

	total energy balance (kWh)	% compare to baseline	air temperature (°C)	% compare to baseline	minimal air temperature (°C)	% compare to baseline	standard deviation (°C)	% compare to baseline
Baseline -no thermal mass added	352.41	0.00%	22.60		4.08		5.30	
with thermal mass	368.70	4.62%	22.61	0.03%	4.95	21.43%	5.68	7.26%

Discussion

Mains results are an increase of the total energy balance of the building (+4.62%), of the minimal air temperature (+21.43%) and the standard deviation (+7.26%) and no change to the average air temperature (+0.03%).

The general conclusions obtained from this experiment are the same as the one obtained for the slab experiment: adding thermal mass to a building increased the minimal air temperature and standard deviation, and did not affect the average air temperature inside the greenhouse. The thermal mass effect played a important role in these results: the fish tanks catch a relative amount of energy during the daytime and then heat the greenhouse at night.

It was concluded that adding fish tanks to the greenhouse (for example by using aquaponics) could benefits the overall energy efficiency of the greenhouse. These conclusions tied up with the conclusions of Thomas and Crawford (2001). They concluded that adding water barrels on the North wall of a greenhouse with a non-glazed, vertical North facing wall of a passive solar designed greenhouse had a beneficial effect to the energy efficiency of the greenhouse. The water barrels were painted black in order to maximize the heat absorption and thus increase the thermal mass effect of the water barrels. This idea could be carried out for hydroponics; however, the software chosen (Design Builder) did not allow such options for the computer modeling.

Wall material study

The goal of this experiment was to determine the most appropriate building material (comparing common building materials in the United States) for the North-facing wall, in terms of energy efficiency of the building. As for the previous experiments, the best materials would generate the highest average air temperature, the highest minimal air temperature and the lowest standard deviation for the average air temperature.

All results of this experiment are presented in appendix.

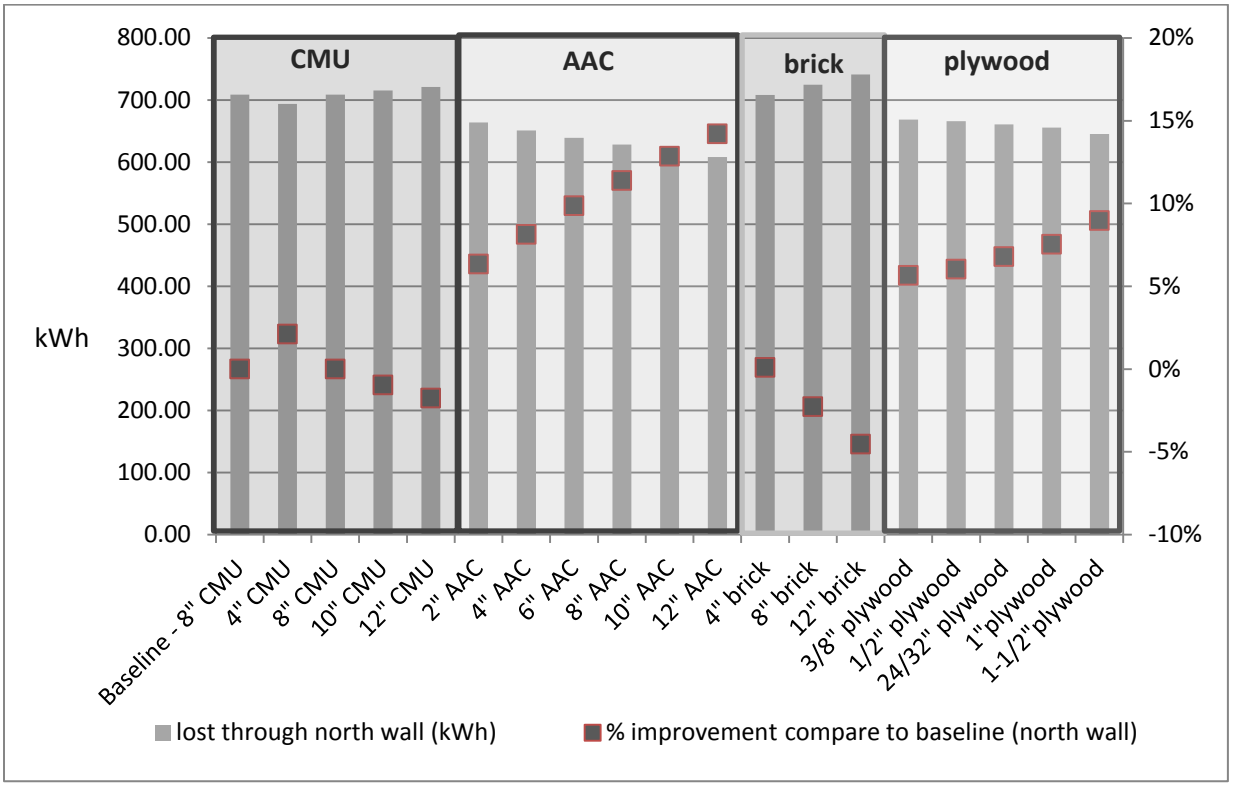


Figure 16.energy losses through the North facing wall for different materials and comparison to the baseline results

Looking at energy losses through the North-facing wall, two different trends appeared depending on the insulating properties of the material. The materials with good insulating properties

(Aerated Autoclaved Concrete and plywood) lead to a decrease of energy losses through the wall as the thickness increased, whereas the other materials (Concrete Masonry Units and bricks) showed the opposite trend.

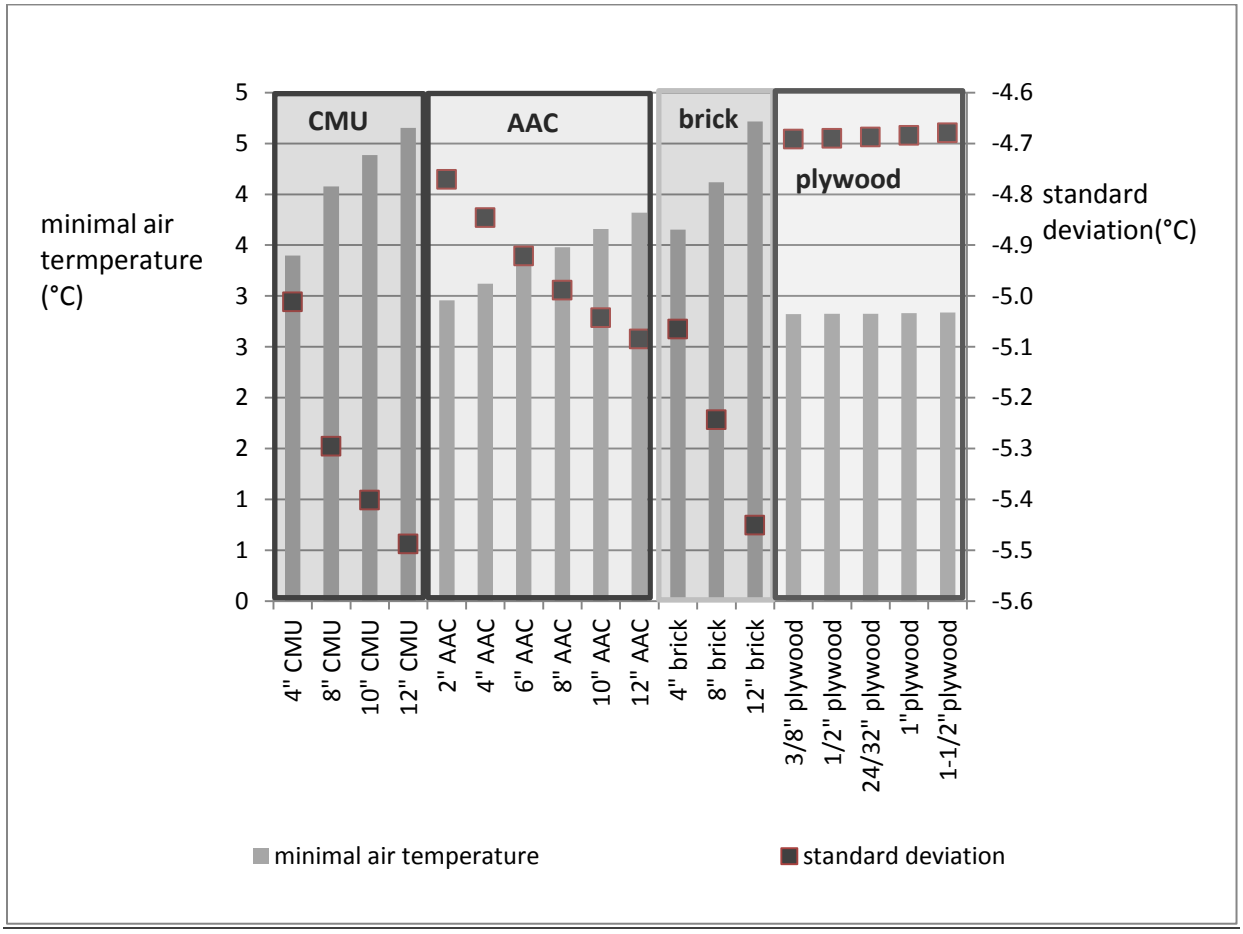


Figure 17. Minimal air temperature and standard deviation of the average air temperature for the different tested materials

Regarding the minimal air temperature and the standard deviation of average temperature, the same trend can be observed for all materials but plywood: increasing the thickness lead to an increase of the minimal air temperature inside the greenhouse and a decrease of the standard deviation of the average air temperature. Concerning plywood, no major change was observed for the minimal air temperature nor the standard deviation of the average air temperature.

Discussion

It seemed that the results of this experiment were linked to the thermal mass or insulating properties of the different materials: AAC and plywood (with good insulating properties) favored the decrease of energy losses as the thickness increased, which was a logical result since increasing the insulation increases the overall R-value of the wall. The other material (CMU and bricks) have high thermal mass properties, that is why the thickness increase is linked with higher energy losses: the wall stored energy during the day and released it at night, and the more material was present the higher this effect was.

The material choice had little or no impact on the average air temperature (variation were under 1%).

The minimal air temperature and the standard deviation of the average air temperature were impacted the same way by the thickness increase of material (the minimal air temperature increased and the standard deviation of average air temperature decreased), except for plywood.

Since the thickness increase was very little for the plywood compared to the other material (variation were under 3cm = 1.2” whereas for the other material variation were over 15cm=5.9”), it was concluded that the variation were not important enough to have a significant impact on the results. However, since the variations corresponds to the panel of thicknesses that is commonly observed for this kind of material, the conclusion that if plywood is chosen as a construction material, the thickness of the plywood panel would have no influence on the minimal air temperature nor the standard deviation of the average air temperature of the greenhouse, and that the results obtained within the range of proposed thicknesses were poor compared to the other materials studied (the highest standard deviation and the lowest minimal air temperature in Figure 17).

Concerning the other material, it was concluded that the largest thickness was suitable regarding the minimal air temperature and the standard deviation of the average air temperature. However, this conclusion had to be balanced by the cost. Indeed, increasing the amount of material for construction increases the cost, which can be a major parameter especially with the brick, which is expensive. This wasn't studied in this paper.

Comparing the different results, it appeared that CMU and bricks have similar behavior (on equal thicknesses they have similar properties in terms of minimal air temperature and standard deviation), and AAC adopted the same trends but in lower extends (the thickness increase has a lower impact on the minimal air temperature or standard deviation). For a given thickness and targeting the minimal thickness, the best material (highest minimal air temperature and lowest standard deviation) was brick, then CMU, then AAC, even if the energy losses were reduced when AAC was employed.

Conclusions

The general conclusions that can be made from these experiments are that passive solar greenhouse can properly grow vegetables during the winter in a climate close to the one observed in the Pacific Northwest.

More detailed conclusions would be specific to each part of the greenhouse that was tested:

- the most suitable material in terms of energy efficiency (measured by average air temperature, minimal air temperature, and standard deviation of the average air temperature) for glazing appeared to be polycarbonates .

- The most efficient shape among those tested was to have a straight South facing roof with a 45° angle with horizontal.

- the best material among those tested was high thermal mass material like CMU or bricks, however this has to be balanced with the cost of these materials.

- adding water tanks to the greenhouse as thermal mass, for aquaponics for example, was a beneficial practice, such as adding a covering blanket at night (outside the greenhouse).

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CHAPTER III. THE RELATIONS OF THERMAL MASS AND INSULATION WITH TEMPERATURE CONDITIONS IN A PASSIVE SOLAR DESIGN GREENHOUSE

Abstract

The present paper focused on the temperature management of a passive solar greenhouse by modifying the amounts of insulation and thermal mass present in the building. To that end, a baseline greenhouse from (Pirou 2011) was modeled in Design Builder/ DOE Energy Plus and its performances over a winter in Eastern Washington, USA were analyzed, and the variation in performances while modifying the insulation and thermal mass in different proportions were compared to the baseline.

The experiences highlighted relationships between average air temperature, minimal air temperature, and standard deviation of the average air temperature on the one hand, and R-value of the slab and width of concrete on the other hand. The kind of relationship unifying these parameters is a logarithmic relationship for the average air temperature and the R-value, and a linear relationship for minimal air temperature, average standard deviation and concrete thickness. The best configuration for slab was the concrete at the innermost layer and insulation at the outermost layer.

These results would help to design a passive solar greenhouse adapted to the plant needs in terms of temperature control.

Introduction

Energy is a key factor while operating a greenhouse: heating can represents more than 30% of the overall operating cost (Coffin 1995). It represents a source of CO_2 emission whatever the heating system is (butane, electrical if not from renewable sources, etc). Focusing on the energy management of a greenhouse can save on cost, and reduce the environmental footprint of the sector.

An easy way to reduce the auxiliary heating requirements is to simply get rid of them. This is the objective of passive solar design, which accepts as only energy source the heat from the Sun, which is sufficient if the building is well designed. Passive solar design greenhouse must be able to provide a healthy environment for plants during the winter without using extra sources of heat but solar radiations.

The most relevant data for a greenhouse study are the average air temperature, because the higher the temperature the faster the plant will grow (Myeni et al, 1997)(Went, 1953) ; the minimum air temperature, because freezing or cold temperature can cause great damage to plants, and the minimal temperature influence the plant growth (Burke, 1976); and the standard deviation because it is related to the temperature variations the plants will have to face (Myeni et al, 1997)(Went, 1953).Thus, the present paper focused on these three parameters.

Reducing the energy need of a greenhouse is not a recent concern: Garzoli (1988) recommended reducing the surface or employing thermal mass. Santamouris et al (1994) proved after a 2year monitoring of a passive solar design greenhouse that it could reduce the energy need by 65%. The energy saving strategy for this greenhouse was to focus on energy storage, by having a lot of

thermal mass on the north facing side and an air to ground heat exchanger. Arinze et al (1984) and Thomas and Crawford (2001) had positive results in utilizing water as a thermal storage.

Thus, a good strategy for achieving passive solar design seems to focus on energy storage and conservation of the greenhouse; that is why this paper focused on thermal mass, insulation, and their relation to the temperature conditions in the greenhouse.

The influence of thermal mass or insulation was studied for a building by Kossecka and Kosny (2001), who studied the heating and cooling loads of a building depending on its wall configuration. Their results were that it was better to have the insulation outside and the thermal mass inside.

Method

Overall approach

The method developed in this paper used the same protocol than what was used in (Pirou 2011), which was based on the Energy Plus modeling of a greenhouse inspired by (Tong et al 2009). The main features were a rounded south facing glazing, with an insulated north wall and slab that acted as thermal mass. A baseline greenhouse was developed, and then the influence of some design modification was analyzed in order to determine what the best option was. The model was run for one typical winter (October to March) in Eastern Washington, USA.

For a more complete description of the general methodology employed, please refer to (Pirou 2011)

Two main experiments were performed. One was focusing on the slab of the greenhouse, and the other one on the wall. Each time, three different configurations were studied, and for each configuration, varying amounts of insulation or thermal mass were employed. The results were then compared one to each other.

Slab study

A set of simulations was performed. The greenhouse in each simulation was the same that the baseline greenhouse presented in (Pirou 2011), but with a different slab. A total of 48 simulations were performed: it corresponds to 3 sets of 16 simulations. Each set is based on a given slab configuration: underslab insulation (insulation under the concrete), overslab insulation (insulation over the concrete), and sandwich insulation (a layer of insulation between 2 layers of concrete). Each set of 16 simulations was composed of 4 groups, each group corresponding to a constant R-value. Values were R-10, R-20, R-30 and R-40 in imperial units (ft^2-F-h/Btu), ie, R-

1.75, R-2.5, R-5.26, R-7 m^2K/W in SI units. For each group of constant R-values, 4 different thicknesses of concrete were tested: 2”, 4” 8” and 12” (corresponding to 5.08cm, 10.16cm, 20.32cm and 30.48cm), and the insulation level adjusted to fit the R-value targeted. Table 5 gives the characteristics of the material used for thermal mass, it corresponds to grouted Concrete Masonry Units (CMU).

Table 5. characteristics of thermal mass employed

parameter	**value**
Conductivity (W/m-K)	1.130
Specific Heat (J/kg-K)	1000
Density (kg/m^3)	2000
Thermal absorptance (emissivity)	0.90
Solar absorptance	0.60
Visible absorptance	0.60

What the slabs were:

- slab 1: underslab insulation (concrete – insulation)

- slab 2: overslab insulation (insulation – concrete)

-slab 3: “sandwich” insulation (insulation – concrete – insulation)

Here is a table helping to understand what simulations were done. There would be 3 different tables like this one, one for each kind of slab (slab1, slab2 or slab3). Each blank case in a table corresponds to a simulation. For example a case located in the slab2 table, on the R-175 row and the 5.08cm column corresponds to a simulation of a greenhouse with a slab of 5.08cm of cast

concrete with insulation over it, adjusted to have a insulation equivalent to R= 1.75 m^2K/W. In this case the walls are 2” concrete based, and the roof and walls have an R-1.75 insulation value.

(slab X)	5.08cm	10.16cm	20.32cm	30.48cm
R-1.75 m^2K/W				
R-2.5 m^2K/W				
R-5.2 m^2K/W				
R-7 m^2K/W				

Wall study

The method employed for this experiment was very similar to the slab counterpart of this experiment: a set of simulations was performed. The greenhouse in each simulation was the same that the baseline greenhouse presented earlier, but with a different slab. A total of 48 simulations were performed: it corresponds to 3 sets of 16 simulations. Each set is based on a given wall configuration: outer insulation (insulation on the outer side of the wall), inner insulation (insulation on the inner side of the wall), and sandwich insulation (a layer of structural material between 2 layers of insulation). Each set of 16 simulations was composed of 4 groups, each group corresponding to a constant R-value. Values were R-10, R-20, R-30 and R-40 in imperial units (ft^2-F-h/Btu), ie, R-1.75, R-2.5, R-5.26, R-7 m^2K/W in SI units. For each group of constant R-values, 4 different thicknesses of concrete were tested, and the insulation level adjusted to fit the R-value targeted.

The slab was purposely not adjusted to the wall configuration; indeed during the slab part of the thermal mass and insulation experiment, the wall was modified for each simulation to fit the R-

value of the slab studied. Hence adjusting the slab to each wall configuration would lead to almost repeat this experiment, which would not be very meaningful.

The material employed for the structure/thermal mass was concrete. It could be CMU (Concrete Masonry Unit) for example or any kind of structural material based on concrete, but for ease of understanding and modeling the results concrete only was chosen since CMU are already a non homogeneous combination of layers of pure concrete and air, which acts as an insulating material.

The performances of the greenhouse were evaluated under the same parameters than the other experiments: average air temperature, minimal air temperature, standard deviation of average air temperature.

What varies: R-value, for each R-value different thickness

What walls:

- wall 1: inner insulation (inside -insulation – concrete - outside)
- wall 2: outer insulation (inside - concrete – insulation - outside)
- wall 3: “sandwich” insulation (inside - insulation - concrete – insulation - outside)

variable: average air temperature, minimal air temperature, standard deviation of average air temperature

Results and discussion

Thermal mass and insulation – slab part

The goal of this experiment was to study the relationship between insulation and thermal mass concerning the slab of a greenhouse, to find the most relevant combination between them for the minimal use of concrete. It aimed at determine how a certain combination of concrete and insulation could influence the environmental conditions in the greenhouse: average and minimal air temperature, losses through the ground, etc.

Results

Slab1: underslab insulation

Complete results summary can be found in appendix, only the temperature graph is shown here since it presents most of the results described in the interpretation part.

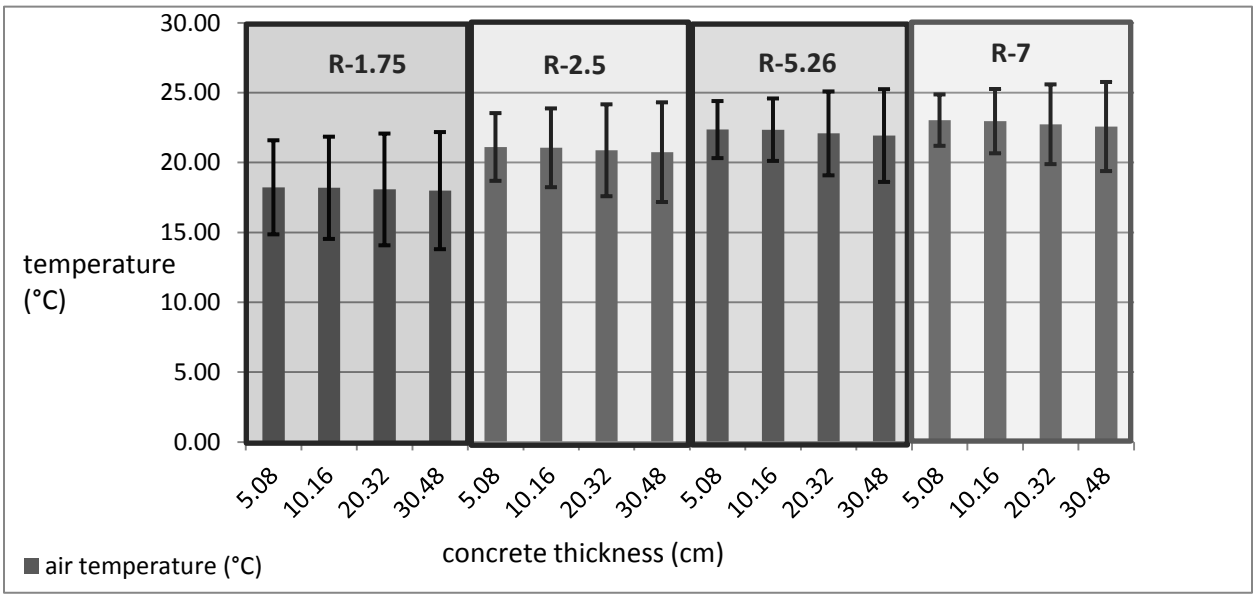

Figure 18. Average temperature in the greenhouse depending on the thickness of the concrete or insulation layers for slab 1 (underslab insulation), based on a whole winter simulation

Interpretation of slab1 results

Talking about concrete thickness, he trend seems to be: “the thinner the better”, regarding both energy loss and air temperature. Indeed, the average air temperature slightly decreases when the thickness of concrete increases, but this trend is very soft and the temperature tends to remain quite constant for a given R-value.

This can be explained by the fact that the thermal mass keeps the slab warm even at night, creating a higher difference in temperature between the inside and the outside and thus leading to higher losses through the ground and loss through radiant heat. This was highlighted in (Pirou 2011), when a covering blanket was added to the greenhouse, and significant reductions in heat losses were observed.

Slab2: overslab insulation

Complete results summary can be found in appendix, only the temperature graph is shown here since it presents most of the results described in the interpretation part.

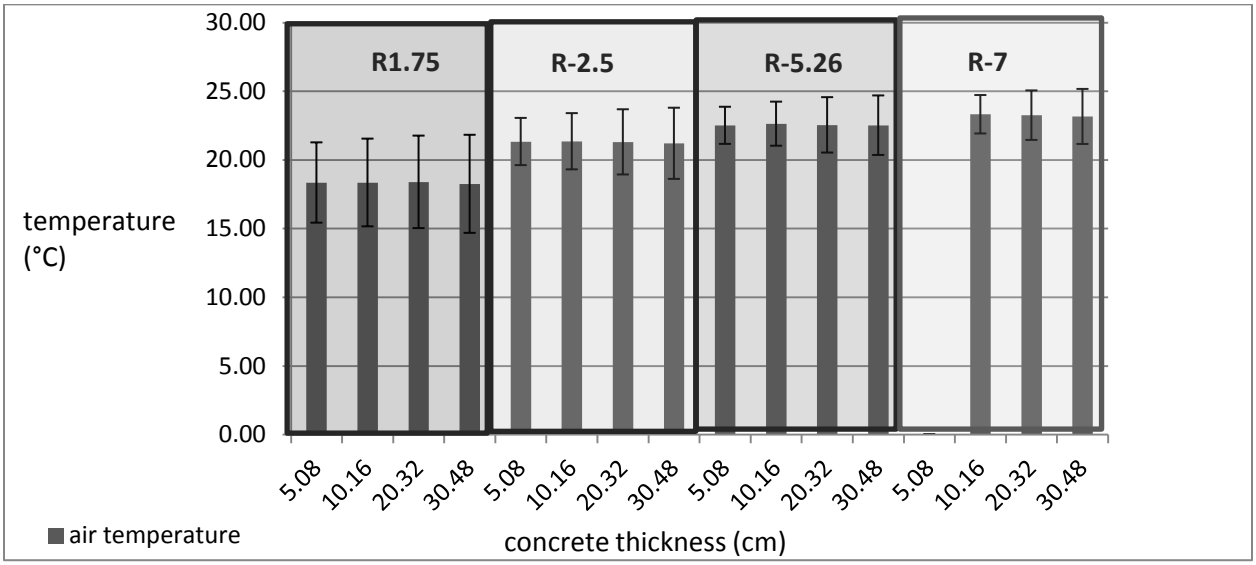

Figure 19. Average temperature in the greenhouse depending on the thickness of the concrete or insulation layers for slab 2 (overslab insulation), based on a whole winter simulation

The R-40 2" of concrete for slab2 didn't work, because the model didn't have enough thermal mass in this configuration and Energy Plus went on fatal error.

Interpretation of slab1 results

The results for each level of insulation follow an hyperbolic tendency with the characteristic curve allure between heat loss and insulation thickness. This is better detailed in the all slab comparison analysis, later in this study.

No significant impact of the difference of thickness of concrete for each level of insulation in terms of air temperature (<0.5%) was observed for this slab configuration.

Slab3: sandwich insulation

Complete results summary can be found in appendix, only the temperature graph is shown here since it presents most of the results described in the interpretation part.

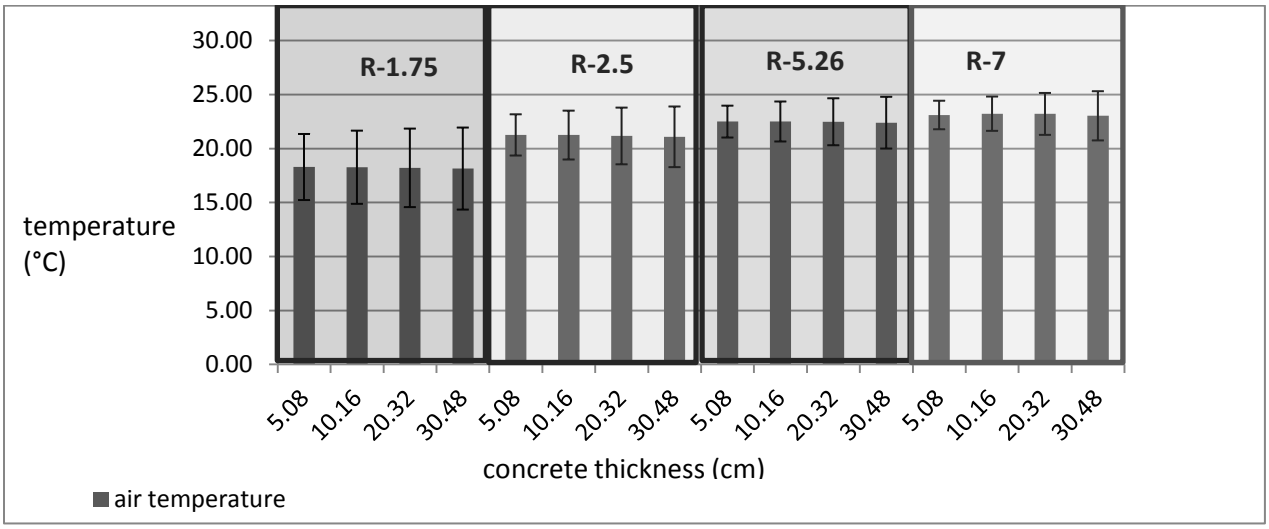

Figure 20. Average temperature in the greenhouse depending on the thickness of the concrete or insulation layers for slab 3 (sandwich insulation), based on a whole winter simulation

Interpretation of slab3 results

Just like the other slabs, the trend seems clearly to be: "the thinner the better", regarding both energy loss and air temperature (especially looking at the standard deviations variations of the temperature average)

A higher insulation level decreases the loss through the wall, and increases the temperature.

Comparison of all slabs

Studying the results, it appeared that the three factors of average air temperature, standard deviation of air temperature and minimal air temperature are related to either the insulation or the thermal mass. The average air temperature in the greenhouse was depending on the insulation level of the greenhouse, whereas the minimal air temperature was closely related to the thermal mass.

For each slab, the temperature averages presented in Figures 18, 19, 20 were averaged based on the insulation criteria: all the temperature calculated based on a greenhouse with a given R-value were averaged, whatever the thickness of concrete and hence the thermal mass was. Concerning minimal air temperature, all the minimal air temperatures simulated for a greenhouse with the same concrete thickness were averaged, regardless the insulation level; a similar process was applied to standard deviations.

The standard deviation of all these averages was also calculated, to measure how reliable these averages were. Then the trend lines establishing what the relationship between the factors is were drawn.

Table 6.comparison tables for the slab part

slab1- underslab insulation

slab 1 - average temperature - no blanket		
R value (m^2K/W)	average of temperature	std dev
R-1.75	18.13	0.11
R-2.5	20.95	0.17
R-5.26	22.19	0.21
R-7	22.84	0.21

slab1 - minimal air temperature - no blanket		
concrete thickness (cm)	min air temp	std deviation
5.08	1.88	0.05
10.16	2.54	0.37
20.32	4.60	0.76
30.48	5.60	0.82

slab1 - standard deviation - no blanket		
concrete thickness (cm)	average standard deviation of air temperature	std dev
5.08	4.84	1.36
10.16	5.51	1.32
20.32	6.57	1.02
30.48	7.13	0.89

slab2 - underslab insulation

slab 2 - average temperature- no blanket		
R value (m^2K/W)	average of temperature	std dev
R-1.75	18.34	0.06
R-2.5	21.30	0.07
R-5.26	22.56	0.05
R-7	n/a	n/a

slab2 - minimal air temperature - no blanket		
concrete thickness (cm)	min air temp	std deviation
5.08	n/a	n/a
10.16	1.83	0.09
20.32	2.50	0.09
30.48	3.33	0.44

slab2 - standard deviation - no blanket		
concrete thickness (cm)	average standard deviation of air temperature	std dev
5.08	n/a	n/a
10.16	1.60	1.60
20.32	1.39	1.39
30.48	1.41	1.41

slab3 - sandwich insulation

slab3 - average temperature - no blanket		
R value (m^2K/W)	average of temperature	std dev
R-1.75	18.23	0.06
R-2.5	21.19	0.08
R-5.26	22.47	0.05
R-7	23.14	0.09

slab3 - minimal air temperature - no blanket		
concrete thickness (cm)	min air temp	std deviation
5.08	1.77	0.04
10.16	2.15	0.06
20.32	3.03	0.26
30.48	3.93	0.42

slab3 - standard deviation - no blanket		
concrete thickness (cm)	average standard deviation of air temperature	std dev
5.08	3.88	1.57
10.16	4.54	1.59
20.32	5.19	1.50
30.48	5.64	1.38

Units: R-value are in ft^2-F-h/Btu, concrete thickness in inches, temperature in °C

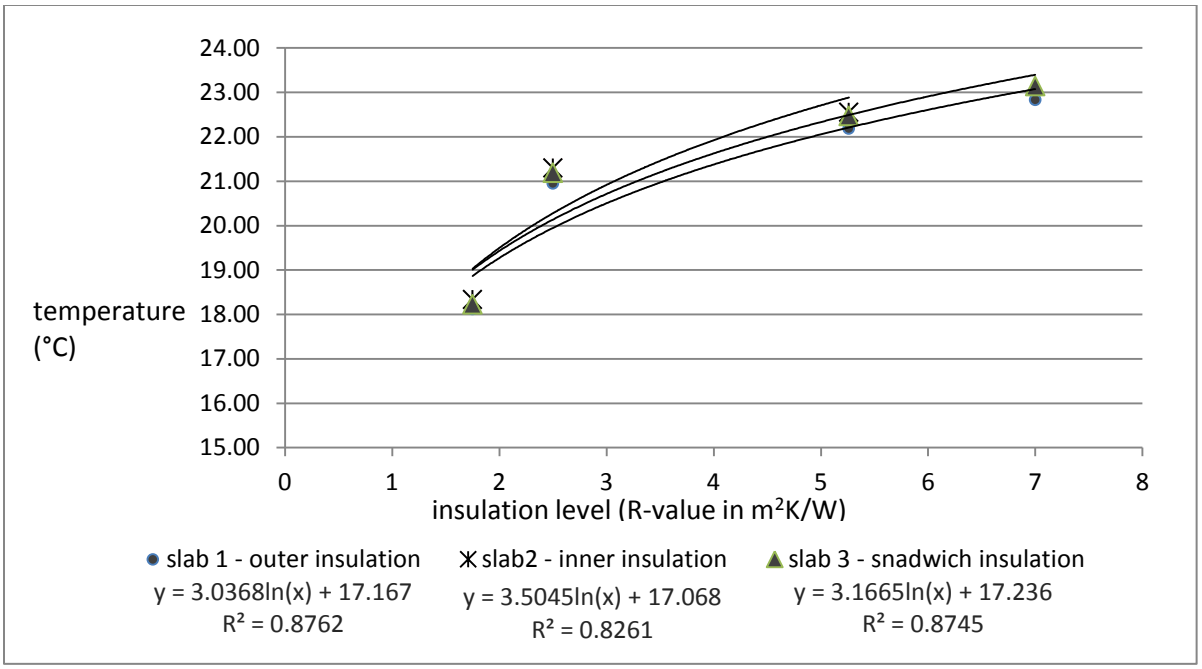

Figure 21. average air temperature depending on insulation level for three different slab types - no blanket added on the greenhouse

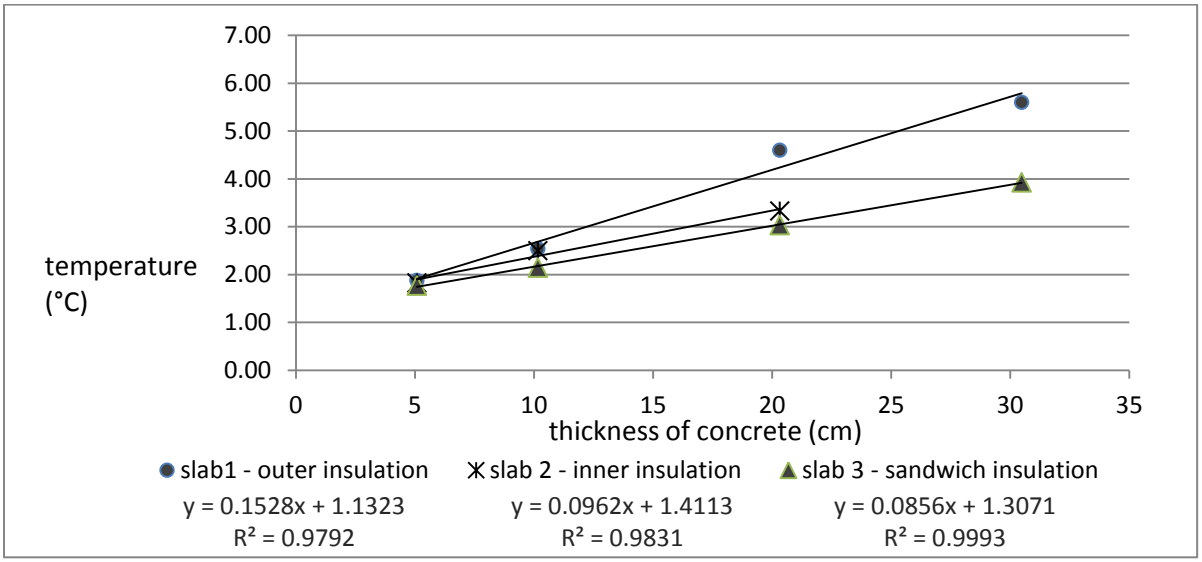

Figure 22. minimal air temperature depending on concrete thickness for three different slab types - no blanket added on the greenhouse

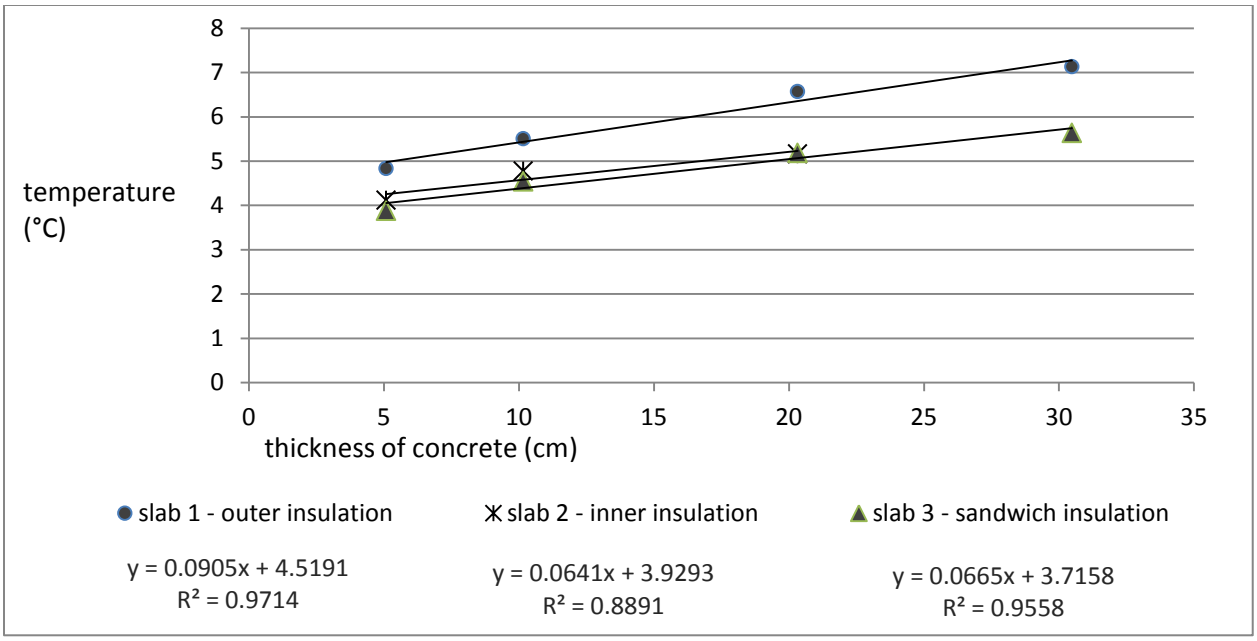

Figure 23. average standard deviation depending on thickness of concrete for three different slab types - no blanket added on the greenhouse

Interpretation of slabs comparison

Average temperature

Looking at the tables and graph related to average temperature, it appears that the average air temperature inside the greenhouse depends only on the insulation level and not on the thickness of the concrete layer for the slab. Indeed, the standard deviation of the averages annual temperature for a constant R-value is always under 0.3°C, which means that the concrete layer thickness has little influence.

The graph shows that the relationship between average air temperature and R-value is a logarithmic relationship. The points on the average air temperature graph (Fig. 21) are following a logarithmic, since the coefficient of determination R^2 is over 0.82 for a logarithmic trendline.

If the insulation is located inside the greenhouse the curve is steeper, meaning that it is more sensible to the insulation level.

The logarithmic relationship can be related to the equation of a temperature profile in a infinite cylinder, assuming that the greenhouse is close to a cylinder shape and that the length of the greenhouse is big compared to its radius:

$$(T_1 - T_2) = \Phi \ \frac{1}{2*\pi*\lambda*L} * \ln\left(\frac{R2}{R1}\right)$$

Where

Φ = thermal flow (in W), difference between the Sun gains and the heat losses occurring in the greenhouse

λ= thermal conductivity in $W.m^{-1}.K^{-1}$ which is constant in this experiment since it is a characteristic of the insulating material used (expanded polystyrene)

L = contact length of the cylinder/greenhouse (in m)

R2 = external radius (in m). Here it corresponds to the insulation thickness *e* adjusted by Design Builder to match the targeted R-value, so R2 = R1+e. e is the variable connected to the insulation level in the graph.

R1 = internal radius (in m). It corresponds to the internal diameter of the greenhouse considered as a cylinder. It is constant.

T1 = average inside temperature (in °C or K)

T2= average outside temperature (in °C or K)

The constant terms of this equation are the thermal flow Φ, the thermal conductivity λ, the length of the greenhouse L and the internal radius R1. The outside temperature doesn't depends on the insulating value, so it can be considered a constant in the equation. It conducts the equation:

$$T1 = \Phi \ \frac{1}{2*\pi*\lambda*L} * \ln\left(\frac{R1+e}{R1}\right) - T2$$

Where e is related to the R-value, and T is the inside temperature of the greenhouse.

Since the experiments show that the average temperature of the greenhouse follows an equation of type:

Average Temperature=A*ln (R-value) + B

Where A and B are constants, we can conclude that the infinite cylinder is a proper model for this greenhouse and that the average temperature in the greenhouse depends only on the insulation of the greenhouse with a logarithmic relationship between average temperature and R-value.

The difference between the three different slabs is little, but it appeared that the insulation located over the concrete layer (overslab insulation, slab 2) maximizes the average temperature over slab 1 and slab 3 (underslab insulation and "sandwich insulation) for a given R-value.

Minimal temperature

Minimal temperature is a key parameter for the plant growth and hence for a greenhouse (Burke et al, 1976). The experiment shows that whatever that overall insulation is, it is always the thickness of concrete layer that really matters. Indeed, the standard deviation for the average of minimal temperatures for a given thickness of concrete whatever the insulation level is always under 15% of the corresponding average minimal temperature. It means that the insulation has little influence on the minimal air temperature in the greenhouse.

The graph shows also a linear relationship between minimal air temperature and thickness of concrete layer, since the trend line connecting all the points is a straight line and the coefficient of determination R^2 is over 0.97 for all the trend lines. Hence, to design a greenhouse, if the critical point is the minimal air temperature, maximizing the thermal mass is a solution to achieve higher air temperature, and it would be more efficient to locate the thermal mass under the insulation.

The location of insulating layer influence how efficient the thermal mass effect of concrete will be: when the insulation is located underslab, increasing the concrete thickness is twice more efficient than if the insulation is located overslab (the steep of the curve is doubled). This correlates the conclusions of Kossecka and Kosny (2001), founding that underslab insulation offers better thermal properties over overslab or sandwich insulation.

Standard deviation of annual temperature average

Looking at the results presented in Figure 21, it appeared the average standard deviation of annual temperature averages relied mostly on the concrete thickness and not on the R-value of the greenhouse. Indeed, the standard deviations of the average standard deviations were low (See table 5). This is due to the thermal effect of concrete which acts as a buffer, catching energy in the daytime and releasing it in the nighttime.

Figure 21 also shows that the relationship between average standard deviation and thermal mass is linear, since the trend line connecting all the points is a straight line and the coefficient of determination R^2 is over 0.88 for all the trend lines.

Similar conclusions as for minimal temperature can be drawn: the location of insulation layer has a large effect on the average standard deviation: if it is located underslab, the buffer effect will be amplified and the standard deviation will be lower than for overslab insulation.

Slab comparison conclusion

This comparison of results provided two different kinds of conclusions:

- Average air temperature, minimal air temperature and average standard deviation depends distinctly on insulation or thermal mass, but not a combination of two. Average temperature relies on insulation, minimal air temperature and average standard deviation depends on thermal mass.

- The kind of relationship unifying these parameters is a logarithmic relationship for the average air temperature and the R-value, and a linear relationship for minimal air temperature, average standard deviation and concrete thickness.

Thermal mass and insulation –wall part

Goal

The goal and methods of this experiment was very similar to the experiment studying the relationship between thermal mass and insulation on the slab level. It aimed at determining the relationship between thermal mass and insulation on the wall level, and thus help to define the best combination between these two parts to maximize the greenhouse performances.

The wall configuration was studied too. Kossecka and Kosny (2001) tested the behavior of a building depending on the wall configuration, and it appeared that the best configuration in terms of energy efficiency was obtained if the insulation was located outside; the present experiment intended to see if such results remains valid for a passive solar greenhouse.

Results

The complete results of this experiment can be found in appendix.

Table 6 summarizes the results averaged according to trends that were observed in the thermal mass and insulation - slab part – study: average air temperature depended on insulation, and minimal air temperature and standard deviation of air temperature relied on concrete thickness. In order to determine if averaging these different values was relevant, the standard deviation corresponding to each average was calculated as well.

The trend lines observed in the thermal mass and insulation - slab part – study were applied to the results: logarithmic trend line for average air temperature depending on insulation level, and linear relationship for the two other studied parameters, each wall separately.

Table 7 . comparison tables for the thermal mass and insulation – wall part study.

wall 1- outer insulation

wall 1 - average temperature

R value	average of temperature	standard deviation
R-1.75	19.47	0.04
R-2.5	21.60	0.00
R-5.26	22.44	0.00
R-7	22.88	0.00

wall 1 - minimal air temperature

slab 1 - thickness of concrete - no blanket	minimal air temperature	standard deviation
5.08	2.66	0.86
10.16	3.08	0.95
20.32	3.93	1.09
30.48	4.54	1.09

wall 1 - standard deviation

concrete thickness	average standard deviation of air temperature	standard deviation
5.08	5.23	0.50
10.16	5.44	0.47
20.32	5.81	0.42
30.48	6.07	0.38

wall 2 - inner insulation

wall 2 - average temperature

R value	average of temperature	standard deviation
R-1.75	19.55	0.00
R-2.5	21.69	0.00
R-5.26	22.53	0.00
R-7	22.98	0.00

wall 2 - minimal air temperature

thickness of concrete	minimal air temperature	standard deviation
5.08	2.36	0.73
10.16	2.33	0.77
20.32	2.35	0.76
30.48	2.39	0.74

wall 2 - standard deviation

concrete thickness	average standard deviation of air temperature	standard deviation
5.08	5.02	0.54
10.16	5.01	0.53
20.32	5.02	0.53
30.48	5.03	0.54

wall 3 - sandwich insulation

wall 3 - average temperature

R value	average of temperature	standard deviation
R-1.75	19.50	0.01
R-2.5	21.65	0.00
R-5.26	22.50	0.00
R-7	22.95	0.00

wall 3 - minimal air temperature

thickness of concrete	minimal air temperature	standard deviation
5.08	2.46	0.81
10.16	2.61	0.81
20.32	2.82	0.76
30.48	2.98	0.70

wall 3 - standard deviation

concrete thickness	average standard deviation of air temperature	standard deviation
5.08	5.09	0.53
10.16	5.14	0.54
20.32	5.21	0.55
30.48	5.27	0.55

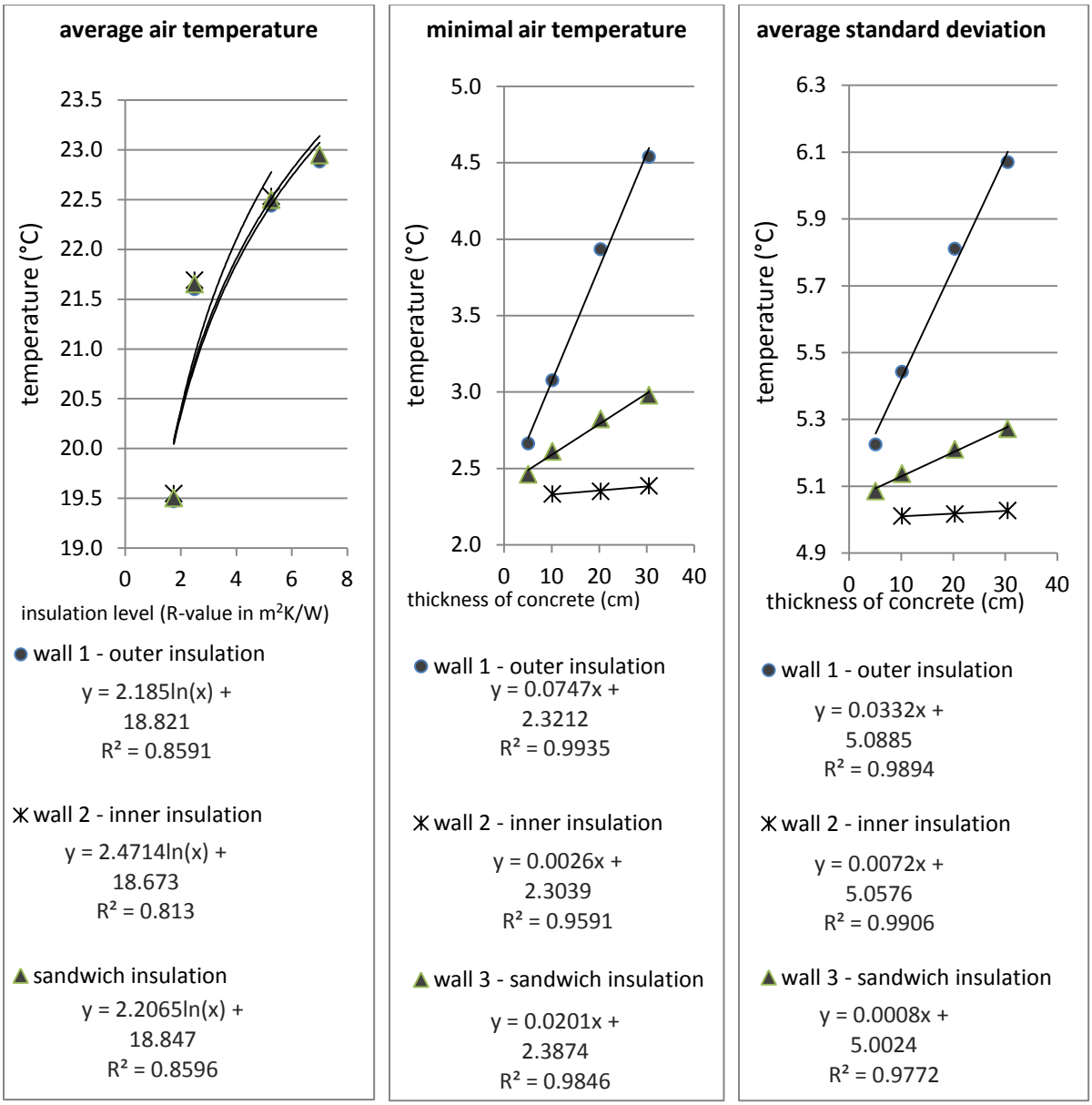

Figure 24. Trendlines of averaged results of the thermal mass and insulation – wall part study. The graphs are the average air temperature depending on insulation (R-value) with a logarithmic trendline, and minimal air temperature and average standard deviation by the thickness of concrete

Interpretation

First of all, it must be noticed that the wall area represents only 25.8% compared to the floor area, which means that the effect of thermal mass or insulation -or their relationship one to each other – in the greenhouse are likely to be predominantly due to the slab rather than the wall. Indeed, these two parts are both composed of layers of concrete and insulation in similar proportions, and the slab had a surface of 181.73m^2 whereas 46.90m^2 for the wall, and so taking the wall and the slab as a block, this block would have a behavior closer to the slab rather than the wall.

This is particularly remarkable when comparing the results of one type of wall compare to the other : it appeared that modifying the concrete thickness for type 2 wall (inner insulation) had almost no effect on the greenhouse behavior, see Figure : the trendline for the minimal air temperature and standard deviation depending on concrete thickness is almost a horizontal straight line, which means that changing the concrete thickness had little or no influence on these parameters. Even while looking at the results for wall 1 (outer insulation, which was proven to be the most sensitive to thermal mass variation in the slab part of the thermal mass and insulation experiment), the tendencies were much lower than what was observed in the slab part of the thermal mass and insulation study: for example the A coefficients for the trendlines presented in figure 24 were two to three times lower than the lowest ones for the slab part of the thermal mass and insulation study.

The standard deviation calculated while averaging the different parameters were also carrying useful information: the averages of air temperature averaged according to the R-value (all the air temperature averages obtained during a simulation with the same R-value were averaged) lead to a very low R-value, and averaging the minimal air temperature and the standard deviations of

average air temperature lead to very high standard deviations. However, the trendlines obtained with these averages gave very high correlation coefficient R^2. It was concluded that the relationship linking average air temperature with insulation on the one hand, and minimal air temperature or standard deviation of average air temperature with thickness of thermal mass on the other hand remained valid, but the influence of slab generated "noise" in the results and tended to minimize the influence of thermal mass of the wall.

Comparing the different results in figure in terms of difference between the wall types, it appeared clearly that the wall type had little influence on average air temperature, but a more sensible influence on the minimal air temperature and standard deviation of average air temperature. These results were logical since as it was tested earlier the average air temperature depends on insulation (and hence the location or even the presence of thermal mass doesn't really matter) whereas the other parameter are more sensitive to thermal mass, and as the effect of thermal mass are increased if it is located inside and the insulation outside. These results matched the conclusions of Kossecka and Kosny (2001), who stated that the best wall configuration was thermal mass on the inner side and insulation on the outer side.

General conclusions for this experiment could be that it confirmed the results obtained in the slab part of the thermal mass and insulation study, but it proved too that the thermal mass of North facing wall has a much lower influence on the greenhouse behavior than the thermal mass of the slab. The insulation has an important role and increasing the insulation level has a noticeable positive effect on the overall greenhouse performances. Hence, designing a passive solar greenhouse should focus on placing thermal mass in the slab, with a coherent insulation of the walls.

Conclusions

The experiences highlighted relationships between average air temperature, minimal air temperature, and standard deviation of the average air temperature on the one hand, and R-value of the slab and width of concrete on the other hand. The kind of relationship unifying these parameters is a logarithmic relationship for the average air temperature and the R-value, and a linear relationship for minimal air temperature, average standard deviation and concrete thickness.

These results could be helpful for designing a greenhouse: depending on what kind of environment is required for plant growth, insulation and thermal mass can be adjusted. Indeed, for each plant there is a minimum, maximum and optimum temperature (Wielgolaski, 1966).

The experience also concluded that the best configuration for wall or slab in a greenhouse was to have the thermal mass on the inner side and insulation on the outer side, matching the results of Kossecka and Kosny (2001).

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Bundle study

Compared to baseline design

In order to make sure that all the results of the experiments performed for this study were relevant and provided significant improvement for the design of the greenhouse, a bundle greenhouse aggregating all the building practices with a positive impact (See table 7) was modeled. The performances of this greenhouse were then compared to the one of the baseline greenhouse.

Table 8. features present in the bundle greenhouse

feature	**Baseline design**	**Bundle greenhouse**
Glazing type	8mm polycarbonate	16mm polycarbonate
Glazing shape	rounded	45° slope
slab	Insulation: R- 5.26 m^2K/W Thermal mass: 20.32cm	Insulation : R-7 m^2K/W Thermal mass: 30.48cm
North facing wall	Insulation: R-5.26 m^2K/W Thermal mass: 20.32cm	Insulation: R-7 m^2K/W Thermal mass: 20.32cm
Covering blanket	no	yes

In order to compare the different results, the parameters used for the other experiments were chosen: average air temperature, standard deviation of the average air temperature and the minimal air temperature in the greenhouse. The complete results based on the same time period as all the other experiments can be found in appendix, but since the months of October and

March showed very high and non realistic temperature in the greenhouse, it was decided not to take them into account and study a shorter time period, from November to February, in order to compare the results only for the coldest months of the year (See Table 8)

.

Table 9. results comparison between the baseline greenhouse and the bundle greenhouse - November to February

	air temperature (°C)	% compare to baseline	standard deviation (°C)	% compare to baseline	minimum air temperature (°C)	% compare to baseline
Baseline -quarter circle	22.60		12.04		4.08	
bundle	25.56	13.09%	10.90	-9.46%	12.90	216.45%

Looking at the different results, the bundle greenhouse showed better performances than the baseline greenhouse: a higher average air temperature (+3°C), a little lower standard deviation (-9.46%) and above all a significant improvement of the minimal air temperature (12.90°C instead of 4.08°C). The climate in the bundle greenhouse was very mild and would allow growing a large variety of plants with no auxiliary heating. This is particularly helpful for the period from mid-February to May, where usually transplant crops are produced and are more fragile, according to Brad Jaeckel, manager of the Washington State University organic farm.

It can be concluded that all these feature put together represented a significant improvement for the design inspired by Tong et al. (2009), and that they are a relevant way to achieve passive solar design.

Compared to regular greenhouse / hoophouse

The next step of the bundle study is to compare the performance of the optimized greenhouse (or bundle greenhouse) with what represents the common practices for greenhouse design: hoophouse and greenhouse. The greenhouse and the hoophouse that were compared to the bundle greenhouse are presented in Figure 25. They have the same footprint than the bundle greenhouse; the materials chosen for the design of these greenhouses were what would be found usually on catalogs or other mainstream commercial products specialized in greenhouse.

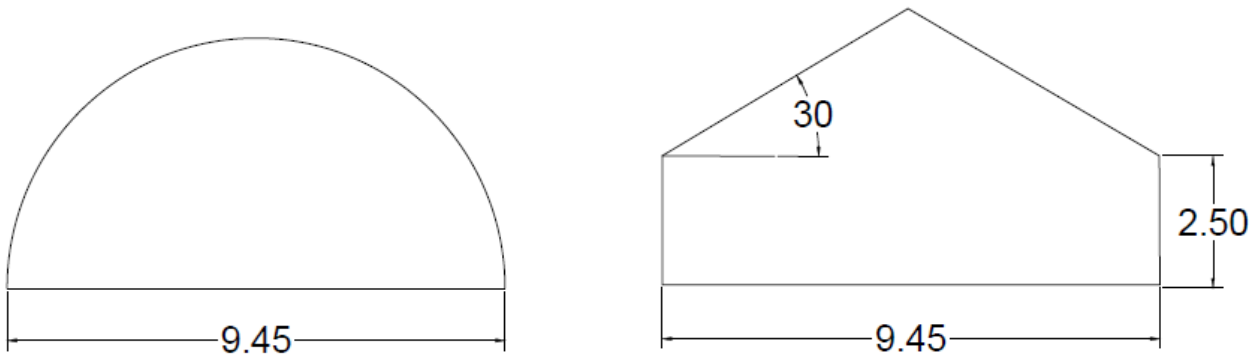

Figure 25. Cross section of the greenhouse and hoophouse tested. dimensions in meters

The hoophouse is covered with polyethylene film, and the greenhouse glazing is polycarbonate 6mm. both have a non-insulated concrete slab (15.24cm = 6”), and are not covered with an insulating blanket at night.

The performances of the bundle greenhouse compared to these two standard greenhouses under the same climatic conditions for the simulation are described in Table 9.

Table 10. Comparison of bundle greenhouse to standard greenhouse and hoophouse

	air temperature (°C)	% compare to bundle	standard deviation (°C)	% compare to bundle	minimum air temperature (°C)	% compare to bundle
bundle	25.56		3.27		12.9	
hoophouse	6.48	-74.66%	5.06	54.89%	-5.47	-142.42%
greenhouse	9.28	63.68%	5.99	83.42%	-2.80	-121.69%

It appeared immediately that the hoophouse and the standard greenhouse are not suitable for passive solar use. Indeed, the inside air temperature went under the freezing point (see the minimal air temperature), which would have killed the plants inside, especially if using fragile plants like transplants or starts, which are commonly grown during the winter in a greenhouse. Moreover, the average air temperature is considerably lower in both case, and the standard deviation is higher.

It was conclude that the bundle greenhouse showed significantly improved performances compared to common practices for greenhouse design, and established proper growing conditions for plants without auxiliary heating need.

Overall conclusions

The general conclusions that can be made from these experiments are that passive solar greenhouse can properly grow vegetables during the winter in a climate close to the one observed in the Pacific Northwest.

More detailed conclusions would be specific to each part of the greenhouse that was tested:

- The most suitable material in terms of energy efficiency (measured by average air temperature, minimal air temperature, and standard deviation of the average air temperature) for glazing appeared to be polycarbonates.

- The most efficient shape among those tested was to have a straight South facing roof with a 45° angle with horizontal.

- The best material among those tested was high thermal mass material like CMU or bricks; however this has to be balanced with the cost of these materials.

- Adding water tanks to the greenhouse as thermal mass, for aquaponics for example, was a beneficial practice, such as adding a covering blanket at night (outside the greenhouse).

- The best configuration for slab and wall were the thermal mass at the innermost layer and insulation at the outermost layer. The thermal mass of the slab has a far greater influence on the greenhouse performance than the thermal mass of the wall.

The greenhouse featuring most of these building practices showed the ability to provide a very mild environment for growing plants, with especially high minimal air temperature and average air temperature. However, it is optimized for temperature conditions, designing a greenhouse would require to take into account other aspects like ventilation, amount of light, etc.

The experiences also highlighted relationships between average air temperature, minimal air temperature, and standard deviation of the average air temperature on the one hand, and R-value of the slab and width of concrete on the other hand. The kind of relationship unifying these parameters is a logarithmic relationship for the average air temperature and the R-value, and a linear relationship for minimal air temperature, average standard deviation and concrete

thickness.

It was also proved that the best configuration for wall or slab in a greenhouse was to have the thermal mass on the inner side and insulation on the outer side.

Other considerations

The bundle greenhouse proposed here is a design that was proven efficient in terms of passive solar design. Indeed, the greenhouse presented as the bundle greenhouse is designed to optimize the temperature conditions, especially the minimal air temperature and the average air temperature in the greenhouse, but it only represents one possibility; other designs might work too.

Moreover, the study performed in the present paper focused on the temperature conditions in the greenhouse, other parameters should be taken into considerations while designing a greenhouse with passive solar requirement, such as the amount of light received by the plants, the ventilation, the functional optimization of the space depending on what is the exact purpose of the greenhouse, etc.

The climatic conditions have a significant impact as well; the experimental setup located the greenhouse in Pullman, Washington (USA), with fixed latitude. The design was proved efficient for this particular climate and position, but it is likely that the design should be adapted to local conditions: higher latitude means a lower angle of incidence for the Sun radiation, and hence a higher angle for the glazed surface. Other local conditions such as predominant winds, relief, amount of snow, etc. should be included in the design process for an optimized greenhouse.

Further research

This study proved that the greenhouse tested with enhanced design was able to provide good growing conditions for plants. But some aspects have not been tested: the influence of plants in terms of energy balance, which would be related to the amount of energy that the plants are absorbing for growing. The amount of light the plants receive during the day should be measured too, in order to determine if they have sufficient light for growth.

A diurnal analysis should be performed too, in order to highlight the thermal mass effect than acts on day-long period of time.

The parameters studied should be tested under different climatic conditions, meaning that the study should be reproduced on a different location to see if the same trends appear as well. For example, according to the common practices in passive solar design, the angle of the south facing roof should be equal to (90 – latitude), hence a study with the latitude of the greenhouse location and the angle of the South facing roof as the varying parameter would be suitable.

Another step for the study would be to focus on the wind conditions: indeed energy is lost through convection as wind is blowing on the greenhouse, and design features addressing the wind control could reduce the energy losses of the greenhouse (low profile greenhouse, wind blocking walls, etc.)

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APPENDIX

Method validation: greenhouse and results

Aquaponics

Overall description of the technique

Aquaponics is based on the combination of two agricultural practices: aquaculture and hydroponics. The first one is intended to raise fish for food production, and the second one is a method for plant fertilizing without using soil as a growing medium. The nutrients needed by the plant are dissolved into water, which pour regularly on the root system of the plant, which are usually in an inert medium like rock wool or clay pellets, or directly in water.

In aquaponics, a symbiosis appears between the plant and fish need and wastes: the fish effluents are used as nutrients for the plants, and thus the water is filtrated from these by-products that are toxic for the fishes. A key point of the system is to have bacteria to convert ammonia present in the fish effluent into nitrite and then nitrate (Rackocy et al, 2006).

This system is still at an early stage of development, but it is gaining interest. For example in the United Sates many organizations promotes this technique, such as Growing Power from Milwaukee, Wisconsin.

How it could be implemented in the studied greenhouse

This design was made based on the technical data provided by S&S Aquafarm. The same size of fish tanks and growing bed was employed: 1.57m (5’2”) high x 2.29m (7’6”) diameter for the fish tanks, and 4.88m (16’)x 1.22m (4’) for the growing beds. Each fish tanks is associated with three growing bed, which form one unit. A total of four maximum units can be implemented in

the greenhouse, but using only three units would be a more convenient use of space since it would allow to have a workspace in the greenhouse.

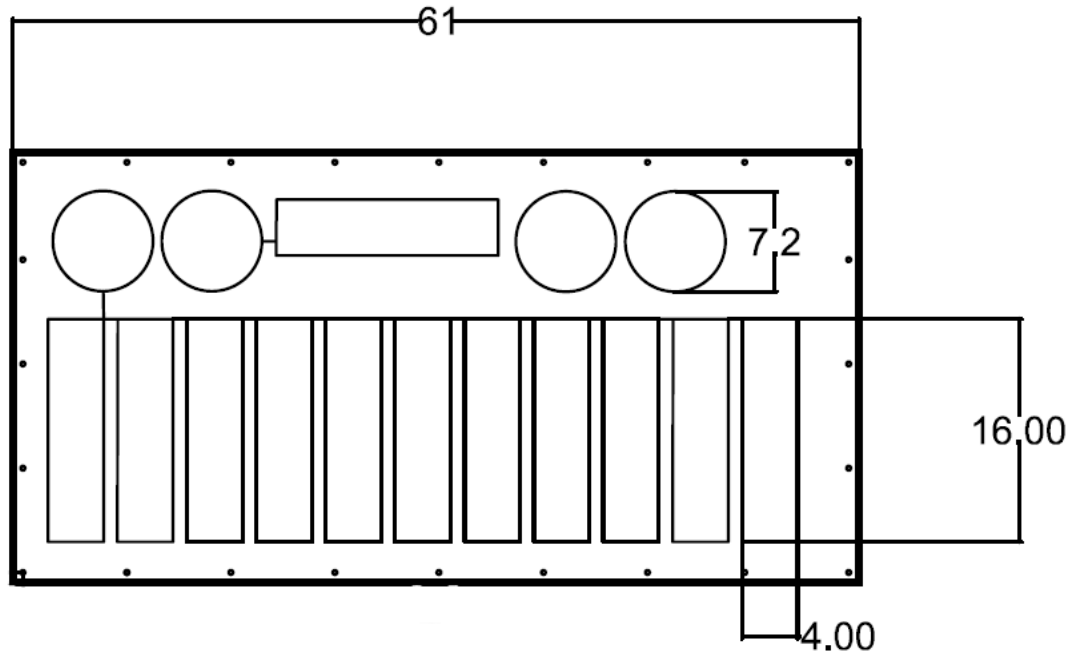

Figure 26. Plans of the aquaponics system implemented in the greenhouse: 4 fish tanks(circles) with 12 growing beds(rectangles). Dimensions in feet

Solutions for energy efficient air exchange

After analyzing the baseline design, it appeared that ventilation and air conditioning is a major source of energy losses (See Figure 5). Changing the design would not influence much this source of losses, since it is more related to the air renewal rate and the temperature of incoming or outgoing air; that is why there is no specific experiment in this paper intending to deal with this aspect of the energy equation. However, the air conditioning system of the greenhouse can be improved in order to reduce the energy losses. Technologies are available for this and some

are presented in the following paragraphs, and it is explained how they could be implemented in the greenhouse.

The existing technologies

Heat/Energy Recovery Ventilation (HRV or ERV)

These systems are based on the process of exchanging the heat (for the HRV) or the heat and humidity (for the ERV) of the exhausted air of a building with the incoming outdoor air. During the winter time, these systems pre-heat and humidify the incoming air, whereas during the summer they pre-cool and de-humidify the outdoor air incoming the building.

Passive or active systems both exist: cross flow heat exchanger, cross plate or rotary heat exchanger for example. A drawback of this kind of system is that it requires more energy than a conventional HVAC system, but it enable to save heating energy and reduce humidity management.

Ground-coupled heat exchanger

Ground coupled heat exchanger (or earth tubes, or earth-air heat exchanger) are a device usually used for pre-treating the incoming air and thus reduce the heat or cooling needs of the building. They are intended to use the quite constant temperature of the ground while going under the surface. The general design is to have the incoming outdoor air run through pipes underground in order to exchange energy with the ground. During the winter, the heat of the ground is transferred to the air and the opposite during the summer.

Such features have been successfully used in greenhouse and showed real improvements for the greenhouse energetic performances: Ghosal et al (2005) determined that using this kind of ventilation could increase the incoming air temperature by several degrees.

An example of application to the studied greenhouse

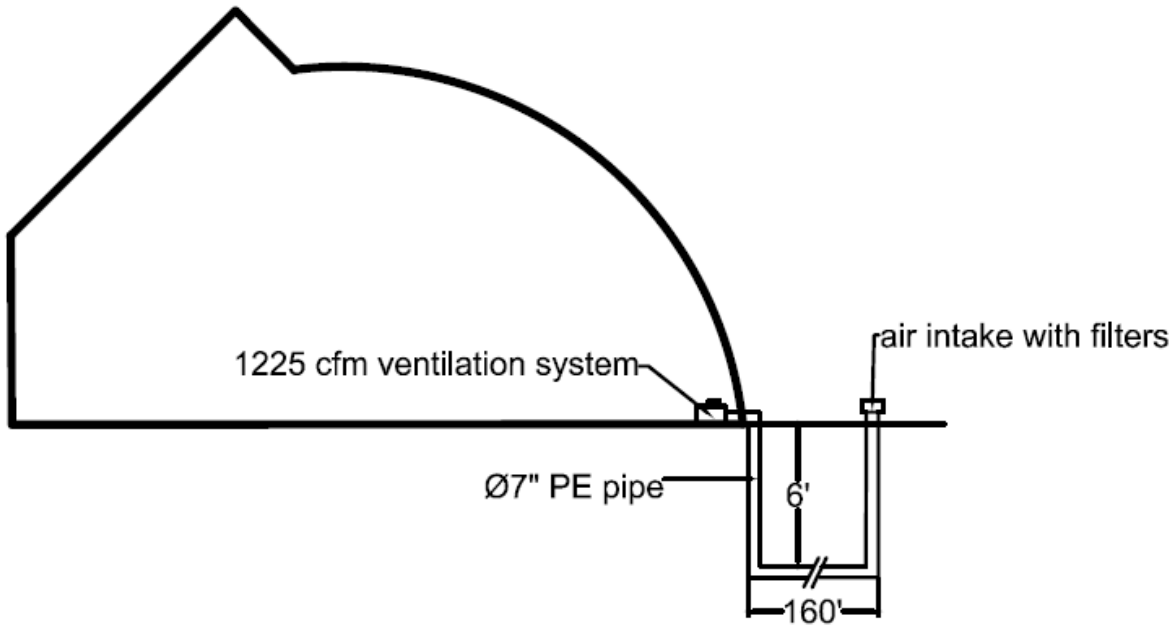

Figure 27.Section view of the greenhouse with the heat exchanger system

A system proposed for the greenhouse ventilation would be a ground coupled heat exchanger, since it proved to be efficient and is cheap and easy to implement.

The volume of the baseline greenhouse is 22,000 cubic feet (594 m^3), associated with an air exchange rate of 2.5 air exchange per hour (all air in the greenhouse is renewed 2.5 times per hour, this is a typical winter practice according to (Buffington et al 1993)). Including a 30% security factor, the ventilation needs require a 1,225 CFM (cubic feet per minute) ventilation system (2,125 $m^3.h^{-1}$).

It would be linked to 160 feet (50m) of PE/PVC tube ,7"(18.06cm) diameter. The length of pipe a common number found in the literature ((Buffington et al, 1993) and others), it depends on the type of soil, humidity rate, etc. The air intake should have some filters, for water, humidity or pest control.

The pipes should be buried at a depth of no less than 6 feet (1.83m). The air exhaust of the system should be close to the gazing, hence it reduces condensation issues on the inner face of the greenhouse.

FULL RESULTS

Glazing study

Glazing material study

Table 11. Glazing study full results: winter average of simulation for various parameters and comparison to the baseline design

	loss through glazing (kWh)	*% compare to baseline*	*total energy balance (kWh)*	*% compare to baseline*	*air temperature (°C)*	*% compare to baseline*	*air temperature standard deviation (°C)*	*% compare to baseline*	*minimum air temperature (°C)*
Baseline - 8mm polycarbonate	37135.04		4103.04		22.60		5.30		4.08
PE film single layer	44294.42	19.28%	4174.67	1.75%	13.27	-23.10%	9.01	70.25%	-0.14
PE film double layer 30mm air gap	29459.05	-20.67%	3690.93	-10.03%	17.95	-11.53%	7.54	42.48%	2.43
PE film double layer 200mm air gap	28924.14	-22.11%	3691.60	-10.03%	18.47	-10.23%	7.39	39.54%	2.72
PE film double layer 30mm air gap x2	19217.34	-48.25%	3383.40	-17.54%	20.23	-5.87%	6.93	30.91%	4.01
PE film double layer 200mm air gap x2	18542.63	-50.07%	3387.89	-17.43%	20.89	-4.24%	6.74	27.20%	4.39
polycarbonate 6mm	37558.20	1.14%	4104.26	0.03%	22.18	-1.04%	5.46	3.08%	3.87
polycarbonate 8mm	37092.04	0%	4103.04	0.00%	22.60	0%	5.30	0%	4.10
polycarbonate 16mm	13299.95	-64.18%	4466.75	8.86%	26.99	10.86%	3.88	-26.64%	6.87
polycarbonate 25mm	13298.49	-64.19%	4466.76	8.86%	26.99	10.86%	3.88	-26.65%	6.87
glass 3mm clear	44241.75	19.14%	4219.90	2.85%	12.30	-25.52%	9.41	77.71%	-0.53
glass low e 3mm 6mm air	19910.57	-46.38%	3050.86	-25.64%	14.62	-19.77%	8.79	65.99%	1.13
glass low e 3mm13mm argon	12233.86	-67.06%	3139.40	-23.49%	17.72	-12.09%	8.07	52.42%	3.30

This table is a summary of the most relevant results among those provided by the Design Builder simulation. Indeed, Design Builder provided a daily average (based on the hourly calculation) for twelve parameters, and only the information that can help to understand the greenhouse behavior are presented here.

Shape of glazing study

Table 12. Results of the simulations for the three different tested greenhouses

	losses through glazing (kWh)	% compare to baseline	total energy balance (kWh)	% compare to baseline	air temperature (°C)	% compare to baseline	standard deviation (°C)	% compare to baseline	minimum air temperature (°C)	% compare to baseline
Baseline - quarter circle	3189.55	0%	352.41	0.00%	22.60		5.30		4.08	
30 degree slope	3792.82	18.91%	213.30	-39.47%	24.79	9.67%	4.41	-16.80%	4.69	15.02%
45 degree slope	3539.33	10.97%	150.77	-57.22%	25.97	14.90%	4.29	-18.95%	5.13	25.90%

Thermal mass and insulation

Thermal mass and insulation – slab part

Table 13. slab1 study full results: winter average of simulation for various parameters and comparison to the baseline design

slab 1 - underslab insulation -no blanket	loss through ground floor (kWh)	% compare to baseline	total energy balance(kWh)	% compare to baseline	air temperature (°C)	% compare to baseline	standard deviation (°C)	minimal air temperature
Baseline	-2456.59	0%	4103.04	0.00%	22.60			
R-1.75 - 5.08cm	-4822.13	-96.29%	4171.57	1.67%	18.23	-19.33%	-6.74	1.96
R-1.75 - 10.16cm	-4963.88	-102.06%	4160.04	2.11%	18.20	-19.48%	-7.32	2.32
R-1.75 - 20.32cm	-5143.21	-109.36%	4189.50	2.11%	18.08	-20.00%	-8.00	3.54
R-1.75 - 30.48cm	-5274.77	-114.72%	4191.31	2.15%	18.00	-20.38%	-8.39	4.49
R-2.5 - 5.08cm	-3083.41	-25.52%	4144.61	1.01%	21.12	-6.55%	-4.85	1.84
R-2.5 - 10.16cm	-3243.51	-32.03%	4145.96	1.05%	21.06	-6.81%	-5.64	2.62
R-2.5 - 20.32cm	-3497.68	-42.38%	4181.52	1.91%	20.88	-7.60%	-6.58	4.61
R-2.5 - 30.48cm	-3696.19	-50.46%	4183.24	1.95%	20.75	-8.20%	-7.14	5.53
R-5.26 - 5.08cm	-2272.92	7.48%	4139.57	0.89%	22.37	-1.04%	-4.08	1.85
R-5.26 - 10.16cm	-2268.92	7.64%	4152.83	1.21%	22.36	-1.07%	-4.47	2.19
R-5.26 - 20.32cm	-2729.13	-11.09%	4180.36	1.88%	22.09	-2.24%	-6.01	5.01
R-5.26 - 30.48cm	-2956.15	0.00%	4181.31	1.91%	21.94	-2.94%	-6.64	6.05
R-7 - 5.08cm	-1812.19	26.23%	4135.43	0.79%	23.04	1.95%	-3.68	1.87
R-7 - 10.16cm	-1988.07	19.07%	4138.62	0.87%	22.97	1.63%	-4.60	3.02
R-7 - 20.32cm	-2294.24	6.61%	4179.75	1.87%	22.75	0.65%	-5.71	5.24
R-7 - 30.48cm	-2528.43	-2.92%	4181.08	1.90%	22.58	-0.07%	-6.38	6.34

This table is a summary of the most relevant results among those provided by the Design Builder simulation.

Table 14. slab2 study full results: winter average of simulation for various parameters and comparison to the baseline design

slab2 - overslab insulation - no blanket	ground floor (kWh)	% compare to baseline	total energy balance	% compare to baseline	air temperature(°C)	% compare to baseline	standard deviation(°C)	minimal air temperature(°C)
Baseline	-2456.59	0%	4103.04	0.00%	22.60			
R-1.75 - 5.08cm	-4555.36	-85.43%	3988.48	-2.79%	18.35	-10.53%	-5.85	1.29
R-1.75 - 10.16cm	-4464.82	-81.75%	4145.52	-1.09%	18.35	-10.52%	-6.39	1.96
R-1.75 - 20.32cm	-4263.37	-73.55%	4058.20	-1.09%	18.40	-10.41%	-6.73	2.20
R-1.75 - 30.48cm	-4412.84	-79.63%	4171.03	1.66%	18.26	-10.76%	-7.14	2.75
R-2.5 - 5.08cm	-3016.78	-22.80%	3187.26	-22.32%	21.34	-3.13%	-3.44	1.65
R-2.5 - 10.16cm	-2971.28	-20.95%	3362.93	-18.04%	21.35	-3.09%	-4.09	1.79
R-2.5 - 20.32cm	-2970.64	-20.93%	3234.35	-21.17%	21.31	-3.20%	-4.75	2.44
R-2.5 - 30.48cm	-2926.91	-19.15%	3383.91	-17.53%	21.20	-3.46%	-5.18	3.25
R-5.26 - 5.08cm	-2192.13	10.77%	3122.45	-23.90%	22.51	-0.21%	-2.70	1.59
R-5.26 - 10.16cm	-2196.67	10.58%	3016.61	-26.48%	22.63	0.08%	-3.21	1.78
R-5.26 - 20.32cm	-2178.03	11.34%	2995.87	-26.98%	22.55	-0.13%	-4.03	2.62
R-5.26 - 30.48cm	-2182.52	0.00%	2844.93	-30.66%	22.52	-0.19%	-4.34	3.57
R-7 - 5.08cm	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
R-7 - 10.16cm	-1736.50	29.31%	2891.70	-29.52%	23.32	1.78%	-2.80	1.78
R-7 - 20.32cm	-1732.96	29.46%	2770.75	-32.47%	23.25	1.62%	-3.61	2.74
R-7 - 30.48cm	-1714.66	30.20%	2877.41	-29.87%	23.16	1.39%	-4.01	3.75

This table is a summary of the most relevant results among those provided by the Design Builder simulation

Table 15. slab3 study full results: winter average of simulation for various parameters and comparison to the baseline design

slab3 without blanket	ground floor (kWh)	% compare to baseline	total energy balance	% compare to baseline	air temperature(°C)	% compare to baseline	standard deviation	minimal air temperature (°C)
Baseline	-2456.59	0%	4103.04	0.00%	22.60			
R-1.75 - 5.08cm	-4543.64	-84.96%	4187.80	2.07%	18.29	-10.67%	6.12	1.83
R-1.75 - 10.16cm	-4541.82	-84.88%	4313.84	4.54%	18.27	-10.72%	6.78	2.09
R-1.75 - 20.32cm	-4563.81	-85.78%	4289.16	4.54%	18.21	-10.87%	7.27	2.67
R-1.75 - 30.48cm	-4624.86	-88.26%	4291.65	4.60%	18.15	-11.03%	7.60	3.38
R-2.5 - 5.08cm	-3040.16	-23.76%	3414.12	-16.79%	21.26	-3.31%	3.82	1.75
R-2.5 - 10.16cm	-3038.09	-23.67%	3613.21	-11.94%	21.25	-3.35%	4.52	2.10
R-2.5 - 20.32cm	-3089.73	-25.77%	3576.93	-12.82%	21.17	-3.55%	5.25	3.03
R-2.5 - 30.48cm	-3128.82	-27.36%	3538.28	-13.76%	21.09	-3.74%	5.62	3.86
R-5.26 - 5.08cm	-2230.76	9.19%	3244.74	-20.92%	22.50	-0.26%	2.95	1.74
R-5.26 - 10.16cm	-2265.44	7.78%	3338.09	-18.64%	22.51	-0.23%	3.70	2.17
R-5.26 - 20.32cm	-2339.73	4.76%	3051.65	-25.62%	22.48	-0.29%	4.35	3.15
R-5.26 - 30.48cm	-2359.36	0.00%	3093.76	-24.60%	22.40	-0.50%	4.79	4.14
R-7 - 5.08cm	-1769.88	0.00%	3262.56	-20.48%	23.11	1.26%	2.64	1.77
R-7 - 10.16cm	-1821.59	25.85%	3147.90	-23.28%	23.23	1.56%	3.18	2.22
R-7 - 20.32cm	-1888.82	23.11%	2825.64	-31.13%	23.21	1.51%	3.88	3.28
R-7 - 30.48cm	-1895.03	22.86%	2969.36	-27.63%	23.03	1.07%	4.56	4.34

Thermal mass and insulation – wall part

Table 16. Results of the thermal mass and insulation – wall part study for wall 1 – outer insulation

wall 1 - outer insulation	north wall (kWh)	% compare to baseline	total energy balance (kWh)	% compare to baseline	Average air temperature	% compare to baseline	minimal air temperature	% compare to baseline	standard deviation	% compare to baseline
Baseline	2418.50	0%	4103.04	0.00%	22.60		4.08		5.30	
R-1.75 - 5.08cm	5905.44	-144.18%	4093.14	-0.24%	19.51	-7.65%	1.46	-64.09%	5.93	12.01%
R-1.75 - 10.16cm	5973.32	-146.98%	4106.63	0.20%	19.50	-7.69%	1.76	-56.83%	6.11	15.36%
R-1.75 - 20.32cm	6103.15	-152.35%	4111.27	0.20%	19.45	-7.79%	2.41	-40.77%	6.41	20.99%
R-1.75 - 30.48cm	6211.97	-156.85%	4112.89	0.24%	19.41	-7.89%	2.99	-26.56%	6.61	24.78%
R-2.5 - 5.08cm	3378.40	-39.69%	4082.87	-0.49%	21.67	-2.31%	2.63	-35.38%	5.21	-1.55%
R-2.5 - 10.16cm	3464.61	-43.25%	4101.50	-0.04%	21.64	-2.38%	3.05	-25.22%	5.43	2.58%
R-2.5 - 20.32cm	3635.35	-50.31%	4110.63	0.19%	21.58	-2.54%	3.91	-4.03%	5.80	9.56%
R-2.5 - 30.48cm	3786.85	-56.58%	4111.66	0.21%	21.52	-2.68%	4.60	12.88%	6.06	14.47%
R-5.26 - 5.08cm	2383.53	1.45%	4080.24	-0.56%	22.51	-0.22%	3.14	-23.00%	4.95	-6.58%
R-5.26 - 10.16cm	2477.66	-2.45%	4098.20	-0.12%	22.48	-0.30%	3.60	-11.71%	5.18	-2.17%
R-5.26 - 20.32cm	2661.35	-10.04%	4109.40	0.16%	22.41	-0.47%	4.54	11.29%	5.57	5.28%
R-5.26 - 30.48cm	2823.70	-16.75%	4110.91	0.19%	22.35	-0.62%	5.14	26.06%	5.86	10.60%
R-7 - 5.08cm	1855.82	23.27%	4080.79	-0.54%	22.96	0.89%	3.42	-16.16%	4.81	-9.15%
R-7 - 10.16cm	1952.84	19.25%	4097.57	-0.13%	22.93	0.81%	3.90	-4.28%	5.05	-4.62%
R-7 - 20.32cm	2146.51	11.25%	4109.51	0.16%	22.85	0.62%	4.88	19.62%	5.46	3.12%
R-7 - 30.48cm	2317.55	4.17%	4110.67	0.19%	22.79	0.46%	5.42	33.06%	5.76	8.69%

Table 17. Results of the thermal mass and insulation – wall part study for wall 2 – inner insulation

wall 2 - inner insulation	north wall (kWh)	% compare to baseline	total energy balance (kWh)	% compare to baseline	air temperature	% compare to baseline	minimal air temperature	% compare to baseline	standard deviation	% compare to baseline
Baseline	2418.50	0%	4103.04	0.00%	22.60		4.08		5.30	
R-1.75 - 5.08cm	5769.56	-138.56%	4136.23	0.81%	19.55	-7.56%	1.36	-66.73%	5.79	9.35%
R-1.75 - 10.16cm	5762.57	-138.27%	4137.34	0.83%	19.55	-7.56%	1.26	-69.11%	5.75	8.66%
R-1.75 - 20.32cm	5764.07	-138.33%	4136.95	0.83%	19.55	-7.56%	1.29	-68.35%	5.77	8.89%
R-1.75 - 30.48cm	5769.56	-138.56%	4136.23	0.81%	19.55	-7.56%	1.36	-66.73%	5.79	9.35%
R-2.5 - 5.08cm	3262.16	-34.88%	4121.01	0.44%	21.69	-2.26%	2.30	-43.57%	5.00	-5.63%
R-2.5 - 10.16cm	3255.76	-34.62%	4121.92	0.46%	21.69	-2.25%	2.31	-43.45%	5.00	-5.61%
R-2.5 - 20.32cm	3254.79	-34.58%	4121.39	0.45%	21.69	-2.25%	2.32	-43.05%	5.00	-5.50%
R-2.5 - 30.48cm	3255.28	-34.60%	4121.83	0.46%	21.69	-2.25%	2.36	-42.18%	5.01	-5.34%
R-5.26 - 5.08cm	2273.16	6.01%	4117.03	0.34%	22.53	-0.17%	2.75	-32.43%	4.72	-10.89%
R-5.26 - 10.16cm	2268.51	6.20%	4117.33	0.35%	22.53	-0.17%	2.76	-32.34%	4.72	-10.90%
R-5.26 - 20.32cm	2267.36	6.25%	4118.45	0.38%	22.53	-0.17%	2.77	-32.06%	4.72	-10.83%
R-5.26 - 30.48cm	2267.13	6.26%	4118.70	0.38%	22.53	-0.17%	2.79	-31.47%	4.73	-10.74%
R-7 - 5.08cm	1748.56	27.70%	4113.88	0.26%	22.98	0.93%	3.01	-26.19%	4.57	-13.60%
R-7 - 10.16cm	1744.87	27.85%	4114.97	0.29%	22.98	0.94%	3.01	-26.13%	4.57	-13.60%
R-7 - 20.32cm	1743.90	27.89%	4115.39	0.30%	22.98	0.94%	3.02	-25.91%	4.58	-13.56%
R-7 - 30.48cm	1743.51	27.91%	4115.56	0.31%	22.98	0.94%	3.04	-25.45%	4.58	-13.49%

Table 18. Results of the thermal mass and insulation – wall part study for wall 3 – sandwich insulation

wall 3 - sandwich insulation	north wall (kWh)	% compare to baseline	total energy balance (kWh)	% compare to baseline	air temperature	% compare to baseline	minimal air temperature	% compare to baseline	standard deviation	% compare to baseline
Baseline	2418.50	0%	4103.04	0.00%	22.60		4.08		5.30	
R-1.75 - 5.08cm	5838.18	-141.40%	4129.62	0.65%	19.52	-7.63%	1.34	-67.22%	5.83	10.14%
R-1.75 - 10.16cm	5861.29	-142.35%	4133.69	0.82%	19.51	-7.65%	1.48	-63.75%	5.90	11.40%
R-1.75 - 20.32cm	5899.41	-143.93%	4136.63	0.82%	19.50	-7.69%	1.76	-56.95%	5.99	13.03%
R-1.75 - 30.48cm	5930.33	-145.21%	4136.88	0.82%	19.49	-7.71%	1.98	-51.39%	6.05	14.18%
R-2.5 - 5.08cm	3309.86	-36.86%	4122.24	0.47%	21.67	-2.31%	2.44	-40.21%	5.08	-4.09%
R-2.5 - 10.16cm	3335.12	-37.90%	4123.74	0.50%	21.66	-2.33%	2.61	-35.94%	5.13	-3.04%
R-2.5 - 20.32cm	3371.93	-39.42%	4124.30	0.52%	21.65	-2.36%	2.85	-30.03%	5.20	-1.71%
R-2.5 - 30.48cm	3406.98	-40.87%	4124.77	0.53%	21.63	-2.39%	3.03	-25.62%	5.28	-0.32%
R-5.26 - 5.08cm	2311.23	4.44%	4119.74	0.41%	22.51	-0.21%	2.90	-28.89%	4.79	-9.59%
R-5.26 - 10.16cm	2333.55	3.51%	4120.49	0.43%	22.51	-0.23%	3.05	-25.13%	4.83	-8.75%
R-5.26 - 20.32cm	2367.83	2.10%	4120.40	0.42%	22.49	-0.26%	3.24	-20.62%	4.90	-7.44%
R-5.26 - 30.48cm	2394.35	1.00%	4120.19	0.42%	22.48	-0.29%	3.36	-17.58%	4.96	-6.27%
R-7 - 5.08cm	1786.39	26.14%	4117.76	0.36%	22.96	0.89%	3.18	-22.10%	4.65	-12.25%
R-7 - 10.16cm	1807.45	25.27%	4117.56	0.35%	22.95	0.87%	3.31	-18.87%	4.69	-11.49%
R-7 - 20.32cm	1838.06	24.00%	4117.89	0.36%	22.94	0.85%	3.45	-15.26%	4.75	-10.23%
R-7 - 30.48cm	1855.28	23.29%	4117.52	0.35%	22.94	0.83%	3.55	-13.04%	4.80	-9.32%

Covering blanket study

Table 19. slab1 with blanket study full results: winter average of simulation for various parameters and comparison to the slab 1 with blanket results

slab 1 - underslab insulation -with blanket	loss through ground floor (kWh)	% compare to baseline	total energy balance(kWh)	% compare to baseline	air temperature (°C)	% compare to baseline	standard deviation (°C)	minimal air temperature
R-1.75 - 5.08cm	5407.63	12.14%	4203.97	0.78%	19.42	6.50%	7.29	3.39
R-1.75 - 10.16cm	5579.93	12.41%	4183.39	0.56%	19.45	6.87%	7.96	3.87
R-1.75 - 20.32cm	5804.59	12.86%	4203.87	0.34%	19.44	7.52%	8.70	5.29
R-1.75 - 30.48cm	5953.62	12.87%	4208.71	0.42%	19.39	7.72%	9.12	6.45
R-2.5 - 5.08cm	3390.21	9.95%	4179.15	0.83%	22.40	6.07%	5.55	3.64
R-2.5 - 10.16cm	3557.96	9.69%	4165.33	0.47%	22.37	6.23%	6.46	4.67
R-2.5 - 20.32cm	3846.02	9.96%	4196.22	0.35%	22.32	6.89%	7.52	6.99
R-2.5 - 30.48cm	4055.58	9.72%	4197.53	0.34%	22.23	7.15%	8.12	8.17
R-5.26 - 5.08cm	2480.10	9.11%	4168.59	0.70%	23.68	5.86%	4.85	3.83
R-5.26 - 10.16cm	2480.68	9.33%	4181.99	0.70%	23.70	5.98%	5.28	4.28
R-5.26 - 20.32cm	2959.96	8.46%	4194.06	0.33%	23.56	6.65%	7.02	7.81
R-5.26 - 30.48cm	3200.60	8.27%	4193.79	0.30%	23.44	6.85%	7.71	8.98
R-7 - 5.08cm	1968.46	8.62%	4164.56	0.70%	24.36	5.74%	4.48	3.95
R-7 - 10.16cm	2145.31	7.91%	4155.66	0.41%	24.30	5.80%	5.51	5.44
R-7 - 20.32cm	2466.45	7.51%	4192.83	0.31%	24.22	6.47%	6.75	8.20
R-7 - 30.48cm	2713.69	7.33%	4192.19	0.27%	24.09	6.65%	7.48	9.42

Table 20 . slab2 with blanket study full results: winter average of simulation for various parameters and comparison to the slab 2 with blanket results

slab 2 - overrslab insulation - with blanket	loss through ground floor (kWh)	% compare to baseline	total energy balance(kWh)	% compare to baseline	air temperature (°C)	% compare to baseline	standard deviation (°C)	minimal air temperature
R-1.75 - 5.08cm	5178.65	13.68%	4082.51	2.36%	19.61	6.86%	-6.16	3.14
R-1.75 - 10.16cm	5134.08	14.99%	4191.76	1.12%	19.69	7.26%	-6.81	3.23
R-1.75 - 20.32cm	4930.23	15.64%	4135.94	1.92%	19.82	7.74%	-7.17	3.58
R-1.75 - 30.48cm	5159.61	16.92%	4139.36	-0.76%	19.71	7.97%	-7.50	4.19
R-2.5 - 5.08cm	3378.02	11.97%	3218.74	0.99%	22.78	6.75%	-3.97	3.20
R-2.5 - 10.16cm	3352.91	12.84%	3370.79	0.23%	22.87	7.09%	-4.75	3.41
R-2.5 - 20.32cm	3064.47	3.16%	3306.69	2.24%	21.70	1.81%	-5.63	3.35
R-2.5 - 30.48cm	3363.94	14.93%	3286.79	-2.87%	22.94	8.16%	-5.75	5.13
R-5.26 - 5.08cm	2443.18	11.45%	3109.75	-0.41%	24.02	6.67%	-3.31	3.27
R-5.26 - 10.16cm	2447.97	11.44%	3092.32	2.51%	24.19	6.87%	-3.96	3.53
R-5.26 - 20.32cm	2449.75	12.48%	3125.30	4.32%	24.22	7.43%	-4.85	4.58
R-5.26 - 30.48cm	2478.26	13.55%	2797.85	-1.65%	24.32	7.96%	-5.02	5.67
R-7 - 5.08cm	1906.93	n/a	3218.93	n/a	24.65	n/a	-3.07	3.33
R-7 - 10.16cm	1917.33	10.41%	3045.86	5.33%	24.89	6.72%	-3.61	3.64
R-7 - 20.32cm	1942.02	12.06%	3033.80	9.49%	25.08	7.84%	-4.61	6.01
R-7 - 30.48cm	1942.02	13.26%	3033.80	5.44%	25.08	8.27%	-4.61	6.01

Table 21. slab3 with blanket study full results: winter average of simulation for various parameters and comparison to the slab 3 with blanket results

slab 3 - sandwich insulation - with blanket	loss through ground floor (kWh)	% compare to baseline	total energy balance(kWh)	% compare to baseline	air temperature (°C)	% compare to baseline	standard deviation (°C)	minimal air temperature
R-1.75 - 5.08cm	5181.98	14.05%	4247.86	1.43%	19.58	7.05%	6.46	3.16
R-1.75 - 10.16cm	5227.92	15.11%	4333.42	0.45%	19.64	7.52%	7.23	3.41
R-1.75 - 20.32cm	5289.67	15.90%	4300.93	0.27%	19.67	8.02%	7.70	4.11
R-1.75 - 30.48cm	5362.25	15.94%	4304.47	0.30%	19.62	8.14%	8.03	4.91
R-2.5 - 5.08cm	3432.62	12.91%	3222.15	-5.62%	22.81	7.27%	4.19	3.29
R-2.5 - 10.16cm	3423.13	12.67%	3580.59	-0.90%	22.81	7.35%	5.15	3.78
R-2.5 - 20.32cm	3532.79	14.34%	3441.36	-3.79%	22.88	8.08%	5.82	4.90
R-2.5 - 30.48cm	3544.63	13.29%	3560.18	0.62%	22.79	8.06%	6.30	5.84
R-5.26 - 5.08cm	2484.82	11.39%	3233.49	-0.35%	24.04	6.84%	3.57	3.44
R-5.26 - 10.16cm	2550.64	12.59%	3115.29	-6.67%	24.19	7.46%	4.24	4.01
R-5.26 - 20.32cm	2616.14	11.81%	3016.29	-1.16%	24.25	7.86%	5.05	5.18
R-5.26 - 30.48cm	2660.17	12.75%	2989.31	-3.38%	24.20	8.07%	5.53	6.33
R-7 - 5.08cm	1962.96	10.91%	3179.33	-2.55%	24.72	6.99%	3.21	3.58
R-7 - 10.16cm	2052.47	12.67%	2826.80	-10.20%	24.95	7.42%	3.78	4.16
R-7 - 20.32cm	2103.30	11.36%	2907.59	2.90%	24.93	7.43%	4.78	5.43
R-7 - 30.48cm	2131.76	12.49%	2807.60	-5.45%	24.90	8.12%	5.27	6.65

Table 22 . comparison table for the averaged results of the blanket study

slab1- underslab insulation

slab1 - average temperature - with blanket

R value	average of temperature	standard deviation
R-1.75	19.42	0.03
R-2.5	22.33	0.08
R-5.26	23.59	0.12
R-7	24.24	0.12

slab1 - minimal air temperature - with blanket

thickness of concrete	minimum air temperature	standard deviation
5.08	3.70	0.25
10.16	4.56	0.67
20.32	7.07	1.29
30.48	8.25	1.31

slab1 - standard deviation - with blanket

concrete thickness	average standard deviation of air temperature	standard deviation
5.08	5.54	1.25
10.16	6.30	1.22
20.32	7.50	0.87
30.48	8.11	0.73

slab2 - underslab insulation

slab2 - average temperature - with blanket

R value	average of temperature	standard deviation
R-1.75	19.71	0.09
R-2.5	22.57	0.59
R-5.26	24.19	0.13
R-7	24.92	0.20

slab2 - minimal air temperature - with blanket

thickness of concrete	minimum air temperature	standard deviation
5.08	3.24	0.08
10.16	3.46	0.18
20.32	4.38	1.21
30.48	5.25	0.79

slab2 - standard deviation - with blanket

concrete thickness	average standard deviation of air temperature	standard deviation
5.08	4.13	1.41
10.16	4.78	1.43
20.32	5.56	1.15
30.48	5.72	1.28

slab3 - sandwich insulation

slab3 - average temperature - with blanket

R value	average of temperature	standard deviation
R-1.75	19.63	0.04
R-2.5	22.82	0.04
R-5.26	24.17	0.09
R-7	24.88	0.10

slab3 - minimal air temperature - with blanket

thickness of concrete	minimum air temperature	standard deviation
5.08	3.37	0.18
10.16	3.84	0.32
20.32	4.90	0.57
30.48	5.93	0.76

slab3 - standard deviation - with blanket

concrete thickness	average standard deviation of air temperature	standard deviation
5.08	4.36	1.46
10.16	5.10	1.53
20.32	5.84	1.32
30.48	6.28	1.24

Units: R values are in ft^2-F-h/Btu, concrete thickness in inches, temperature in °C

Equations are of type A*ln(x)+B or A*x+B with A or B constants, they are the coefficients described in this table. The %change refers to the percentage of difference between the coefficient related to "with blanket" compared to the "no blanket situation"

$$\% \text{ change} = \frac{(coefficient \text{ with blanket} - coefficient \text{ no blanket})}{coefficient \text{ no blanket}}$$

Table 23. offset generated by the addition of a covering blanket at night, occurring on the different graphs of average air temperature, minimal air temperature and standard deviation.

	average air temperature				**minimal air temperature**				**standard deviation**			
type	*A coefficient*	*% change*	*B coefficient*	*% change*	*A coefficient*	*% change*	*B coefficient*	*% change*	*A coefficient*	*% change*	*B coefficient*	*% change*
slab1 - no blanket	3.04		17.17		0.15		1.13		0.09		4.52	
slab1 - with blanket	3.11	2.30%	18.45	7.45%	0.19	26.67%	2.82	149.56%	0.1	11.11%	5.19	14.95%
slab2 - no blanket	3.5		17.07		0.09		1.41		0.06		3.65	
slab2 - with blanket	3.43	2.00%	18.48	8.26%	0.08	-11.11%	2.73	93.62%	0.06	0.00%	4.03	10.42%
slab3 - no blanket	3.17		17.24		0.1		1.31		0.07		3.72	
slab3 - with blanket	3.38	6.62%	18.59	7.26%	0.09	-10.00%	2.83	116.03%	0.07	0.00%	4.19	12.64%
averages		**3.64%**		**7.66%**		1.85%		119.74%		3.70%		12.67%

Material study

Table 24. averaged results of the material study experiment

	Energy losses through north wall (kWh)	% compare to baseline	total energy balance (kWh)	% compare to baseline	air temperature	% compare to baseline	minimal air temperature	% compare to baseline	standard deviation	% compare to baseline
Baseline - 8" CMU	2418.50	0%	4103.04	0.00%	22.60		4.08		-5.30	
4" CMU	2367.45	2.11%	4090.69	-0.30%	22.62	0.04%	3.40	-16.67%	-5.01	-5.36%
8" CMU	2418.50	0.00%	4103.04	-0.01%	22.60	0.00%	4.08	0.00%	-5.30	0.00%
10" CMU	2441.81	-0.96%	4102.62	-0.01%	22.59	-0.02%	4.39	7.62%	-5.40	2.00%
12" CMU	2460.94	-1.75%	4103.20	0.00%	22.59	-0.03%	4.65	14.17%	-5.49	3.63%
2" AAC	2265.13	6.34%	4095.84	-0.18%	22.64	0.10%	2.96	-27.43%	-4.77	-9.91%
4" AAC	2221.84	8.13%	4097.34	-0.14%	22.66	0.15%	3.12	-23.44%	-4.85	-8.49%
6" AAC	2179.96	9.86%	4104.20	0.03%	22.68	0.20%	3.30	-19.12%	-4.92	-7.07%
8" AAC	2143.15	11.39%	4104.74	0.04%	22.70	0.24%	3.48	-14.64%	-4.99	-5.80%
10" AAC	2107.65	12.85%	4104.92	0.05%	22.72	0.29%	3.66	-10.24%	-5.04	-4.77%
12" AAC	2074.91	14.21%	4104.83	0.04%	22.73	0.33%	3.82	-6.29%	-5.08	-3.98%
4" brick	2416.17	0.10%	4076.12	-0.66%	22.71	0.28%	3.65	-10.44%	-5.06	-4.35%
8" brick	2473.49	-2.27%	4079.80	-0.57%	22.74	0.35%	4.12	1.05%	-5.24	-0.99%
12" brick	2528.22	-4.54%	4081.01	-0.54%	22.73	0.31%	4.71	15.65%	-5.45	2.93%
3/8" plywood	2281.71	5.66%	4116.72	0.33%	22.63	0.07%	2.82	-30.75%	-4.69	-11.41%
1/2" plywood	2272.57	6.03%	4116.40	0.33%	22.63	0.08%	2.82	-30.71%	-4.69	-11.43%
24/32" plywood	2254.28	6.79%	4117.17	0.34%	22.64	0.10%	2.83	-30.67%	-4.69	-11.48%
1"plywood	2236.26	7.54%	4116.83	0.34%	22.65	0.12%	2.83	-30.58%	-4.68	-11.54%
1-1/2"plywood	2201.60	8.97%	4116.25	0.32%	22.66	0.16%	2.84	-30.40%	-4.68	-11.64%

Location of the covering blanket

Table 25. Averaged results of the covering blanket study

	losses through glazing (kWh)	% compare to baseline	total energy balance	% compare to baseline	average air temperature	average air temperature: variation in % compare to baseline	standard deviation	standard deviation: reduction in % compare to baseline	minimal air temperature	% compare to baseline
Baseline -no blanket	37135.04	0%	4103.04	0.00%	22.60		5.30	0	4.08	
blanket inside	33559.65	9.63%	4462.05	8.75%	25.13	6.28%	4.78	9.68%	5.94	45.80%
blanket outside	32727.44	11.87%	4155.51	1.28%	26.90	10.64%	4.52	14.61%	7.10	74.22%

Bundle greenhouse

Table 26. results comparison between the baseline greenhouse and the bundle greenhouse – full winter results

	air temperature (°C)	% compare to baseline	standard deviation (°C)	% compare to baseline	minimum air temperature	% compare to baseline
Baseline - quarter circle	22.60		5.30		4.08	
bundle greenhouse	33.95	50.21%	3.27	-38.28%	12.90	216.45%