An Energy Efficient Mini-Greenhouse for Seedling Production

Design Project BREE495

by

Francois Handfield

Gabriel Panaccio

Oliver Stark

Fall 2006

McGill University, Macdonald Campus

McGill

ACKNOWLEDGEMENTS

We would like to thank sincerely certain professors of the department of Bioresource Engineering and Plant science of McGill University, who gave generous and helpful advices, comments and suggestions for certain parts of the project, notably Dr. V.Raghavan, Prof. D.Weiss, Dr. N.Wang , Dr. Samson Sotocinal. and Scott Mantelkow.

ABSTACT

Starting the seedling production in an adverse northern climate is quite challenging. Seeds are influenced by large temperature difference and are prone to deterioration. Controlling the environment to enhance the seedling production is the objective of this project. Energy efficiency is another goal. The design relies on water as a heat storage-exchange medium, since this fluid has the largest heat storage capacity and is easily available. The potential of moisture removal from condensation is also attractive. Many types of home and small greenhouse exist on the market, but none is automated. Our prototype would have sensors and probes in order to computerize data and be capable of controlling and predicting the greenhouse responses to the different environmental stimuli. The world is on the verge of an oil crisis and we need to rethink tomorrow's way of living. The food industry needs to get back into people's home in order to facilitate access to resources and healthy food. The mini-greenhouse could also serve in remote environments and villages, such as in the Arctic.

Many different parameters have to be considered and calculated. The different modes of heat transfer and the type of heat exchanger would have to be assessed in order to determine the sizes of the devices, such as the volume of water basin and motor power. In addition to heat transfer, the condensation process and fluid flow in the greenhouse are important factors to establish. Data, such as humidity and temperature ranges, related for the plant under study would need to be gathered.

Materials should be chosen according to their costs, efficiency, availability and constructability. However, the ultimate goal is to be as inexpensive and constructible as possible. Electronic devices to monitor humidity and temperature could be added to the design and should be chosen for the same reasons as the different materials. The greenhouse was built at the Agricultural Engineering Workshop on Macdonald Campus. The testing was conducted inside the shop with the help of thermocouples and a computer for data collection. Tested and theoretical values both show an increase of water temperature of 2ºC in 8 hours. Moreover, the temperature inside the greenhouse was much higher than outside the greenhouse, averaged 20ºC, and this was only due to the light source. More results

indicated that the temperature of the air leaving the heat exchangers was at the same temperature as the temperature of the water in the tank. Many design considerations and manipulation errors could explain the slight differences between theoretical and experimental results. Many assumptions were taken into account in our calculations, the type of heat exchanger could also be a cause of discrepancy. In the light of these results, improvements are proposed for future work.

TABLE OF CONTENTS

1. INTRODUCTION

Seedling production starter systems are known to have a whole set of problems on their own. Hence, seedlings need more attention than more mature plants; they are much more sensitive to environmental fluctuations and most of all they need a well scheduled watering plan. Unless using some form of automation, these tasks can be very time consuming and irregularities in care will lead to mostly irreversible adverse effects, sometimes death of the plants. The analogy with human beings can be readily established, where it is common knowledge how well a baby needs to be cared after.

However unlike babies, seedling starting can be automated. It is worthwhile to note that most parameters having an effect on seedling and plant growth are well documented in the scientific literature making these parameters well suited for automated surveillance and management. The extent to which this automation goes will only be determined by the added complexity one wishes to deal with. An entirely automated system can be imagined but most likely a balance between automation and some basic human interaction will lead to the most efficient design. This project is an attempt to put our engineering knowledge to contribution to design and construct a greenhouse with integrated heat storage while running on a rather tight budget. The automation of a greenhouse is quite complicated and could be a project by itself. Due to time constraint and lack of expertise we focused here on the Phases I and II of the project: design of heat transfer system, components design and implementation of the greenhouse.

Optimal growing conditions are often realized in our climate in greenhouses. A great deal of the operating costs is associated with complementary heating necessary to maintain these optimal growing conditions. In today's energy climate, efficiency is more of a concern than ever. Traditional greenhouse operations often have inherently inefficient designs. During the day, temperature most likely reaches levels that are too high and ventilation is required to get rid of the excess heat and moisture. On the other hand, temperature is most likely to fall below optimum levels during the night so complementary heating is required. This tendency is further amplified during the colder seasons. Many greenhouse producers choose not to invest in a heating system but still need to start their seedlings in late winter early spring. Unfortunately, no common system is available to help them to do so inside an unheated greenhouse. Efficient operation is more than welcome and tapping into the excess heat during the daytime and storing it for release during the night time would be the most straightforward solution. We looked into these possibilities and ultimately implemented one possible engineering design to achieve storage of excess heat and release of the stored energy.

In a cold climate, the length of the growing season basically determines the kind of crop that can be grown. Greenhouses also enable the extension of this growing season or in some cases will even allow year around operation. Once again, the economics are the main factors determining whether such year around operation is indeed possible. Efficient energy use in the greenhouse will have a definite impact in this area. Moreover, we all know that the first producers out on the market to sell their yields are making lots of money. It is the same situation with the producers who sells all year round, who can sell at higher price.

2. PROBLEM STATEMENT

2.1 What is the setting and history behind this project?

When we want to grow plants off-field or semi-outdoors, we often use a greenhouse or a tunnel, which is a controlled environment that harvests sun's energy. Generally, a greenhouse is large enough so that a human can enter into and relatively large plants can grow inside it. Other scales of greenhouses are generally not encountered, although in many cases relatively small plants are greenhouse grown. Also, many market gardeners choose not to invest large amounts of money involved in a heating system, even if it becomes impossible for them to produce their own seedlings. If they could make efficient use of their unheated greenhouse to grow their seedlings early in the season, it would lead to a better energy efficiency and economic profitability. Besides that, there is a need, especially in Quebec, for better energy efficiency in greenhouse production. Since the current trend is to reduce fossil fuel consumption, solar energy should be used in the most efficient way possible in greenhouse production.

2.2 What is the problem to be addressed?

More efficient use of solar energy in greenhouse production is a way to have more sustainable production. A lot of this energy is wasted in several ways; however it is possible to find solutions to take care of some of these losses. The problem that often arises is that a whole greenhouse needs to be heated for the growth of plants that would only require limited amount of space, thus leading to inefficient energy use. The special case of growing seedlings in a greenhouse in an energy efficient manner is the main focus of this project, particularly when radiation is abundant during the day and nights are cold. Automated operations will also enable us to react to operational parameter variations in a timely fashion, minimizing unnecessary temperature fluctuations.

2.3 What are some current approaches to this problem?

One common way of controlling the environment locally for seedlings in a greenhouse is to grow them on a heating table, on which there is generally a layer of sand containing heating cables (Rodrigez, 2004). Some producers even build small tunnels inside the greenhouse to get early produce and remove them once the crop needs more space. Transparent covers are sometimes put over seedling trays so as to trap more energy around the plant. When plants do not grow tall, thermal blankets are often used to reflect back the outgoing radiation overnight (University of Arizona, 2002). Passive short-term energy storage is sometimes done by storing excess heat encountered during the day in a mass of water, soil, mud, rocks (Anonymous, 1978; Basçetinçelik et al., 2003; Bernier, 1987; Kürlü et al., 2002; Ménard, 1991)... It is then released overnight the environment surrounding the crop.

2.4 How will our attempt be better than previous approaches?

We will address the special case of a mini-greenhouse that could be operated either inside a bigger greenhouse or as a stand alone unit, which is an improvement that is rarely seen. This can help in making a more efficient use of solar energy than the usual large greenhouses. Our small greenhouse space enclosing seedlings will be used more intensively. This microenvironment will better control excess heat losses and moisture and will achieve heat storage more easily.

2.5 Solutions previously considered

During the first weeks of brainstorming several ideas came to our mind and they will be summarized below.

The glazing of the mini-greenhouse can be made out of several materials, most likely glass, rigid plastic or soft plastic. They can have various structural, insulating, reflective or photo-selective properties and the shape can be round or straight with angles. Several layers of cover can be superposed.

The heat storage mass can consist of several materials, water being a very interesting one because of its heat capacity, ease of use and availability. Stones, mud and soil can also be used, but their heat capacity is less than that of water. The heat exchanger between the air of the mini-greenhouse and the mass of water has to be designed. High surface availability at the air interface is a must in order to achieve a good heat transfer rate. It is possible to make the water flow inside the greenhouse: inside pipes or between two layers of glazing (Menard, 1991). It is also possible to make the air of the greenhouse flow in the water mass: in pipes or as bubbles.

We have to remove excess moisture as well. This can be done in two ways: ventilation and condensation, which can happen in the heat exchanger when the mass of water is significantly colder than the air. This solution is indeed preferred to ventilation as the latter might lead to significant energy losses to the outside.

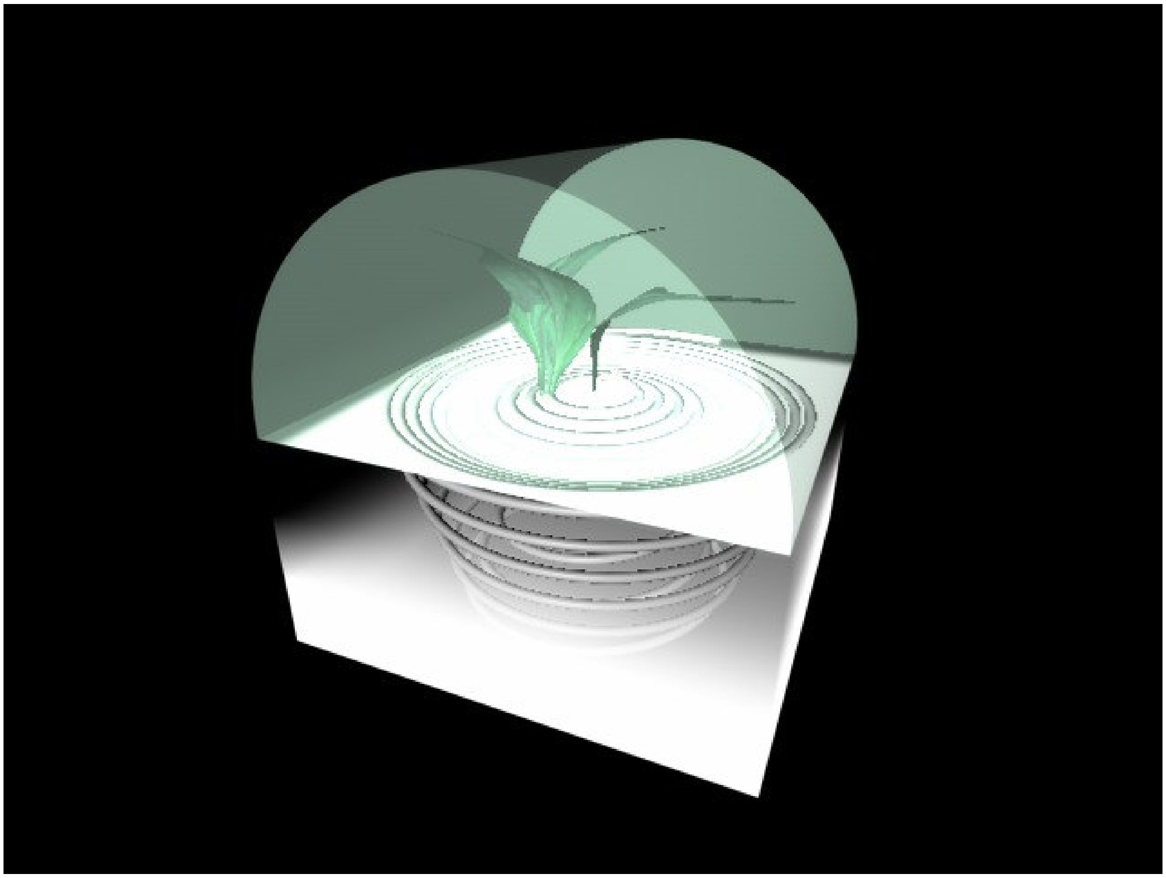


Figure 1: Conceptual mini-greenhouse

3. METHODOLOGY

3.1 Design Process

Any engineering design has to go through a strict process. There are many steps in the implementation of a product. All these steps must be fulfilled in order to have a good design. In our case, we have to think about the design, testing, feasibility, manufacturing and the production and operating cost of the product. We are well aware that bioresource engineering has to satisfy a market that is suffering from globalization and competition, meaning that a cheap and efficient design is to be considered. The problem identification has been described in the previous section. As a team of engineers, we had to hold many brainstorming sessions in order to come out with preliminary design ideas and sketches. The goal was to generate new thoughts and revolutionary designs. Then, we gathered some of the best ideas to form what is a fairly accurate design of a mini-greenhouse. A preliminary design of the greenhouse is shown in Figure 1 above. In the case of an undergraduate design project, we did not have the time and resources that would have companies or graduate students. Hence, the testing and analysis of results and the possible redesigning occurred in a circular, trial and redesign fashion. The structural frame will be constructed in the workshop on the Macdonald Campus of McGill University. This will assure that we use the proper tools to implement the different parts.

3.2 Sources of information

Greenhouse management and controlled environment literature is exhaustive. Most of the information was found in scientific articles and research thesis. For instance, Hervé Bernier, a former student from the Department of Bioresource Engineering at McGill University, wrote a complete document entitled "Energy conservation using a soil heat exchanger-storage in a commercial greenhouse" (Bernier, 1987). Substantial research about heat storage for greenhouses has also been done in the United-States, Holland, Turkey, Greece, Sweden, Japan and Canada. Material description, prices and catalogues with data are available online and all information can be downloaded. Among other useful sources of information, there is a free online greenhouse management course offered by the University of Arkansas, at http://www.uark.edu/~mrevans/4703 (University of Arizona, 2002).

3.3 Scope of study

This project was conducted in the scope of the design project course. It had mainly an academic purpose, but the project was also designed with the ultimate goals of implementing, testing and using it. As outlined in the section above, the small size of the seedlings doesn't justify a full size greenhouse structure. At the same time, the dimension of the greenhouse shouldn't interfere much with maintenance and monitoring tasks. For this reason, the greenhouse was built on a platform no larger than 1 m^2 where things would be at arm's reach. The heat storage was achieved by the use of water due to its high heat capacity. Water was stored in an insulated storage compartment positioned right under the greenhouse platform. The upper part of the greenhouse would of course accommodate a transparent glazing to let the light come through but retain heat as much as possible inside the greenhouse. The exact nature of the best glazing could be researched later on. The actual glazing was subjected to cost and availability constraints.

The greenhouse should be able to function as a year around seedling starter greenhouse with a special emphasis put on early and late winter operation. Winter operation should be as autonomous as possible with sporadic external heat input in the case when stored energy would prove to be insufficient. Operational parameters were calculated for Quebec, in the 4-5 plant hardiness zones.

Automation was of course an integral part of the project, its ideal extent being dependent on the cost/benefit analysis that will be carried out later. We would have liked to implement at least a temperature and moisture monitoring inside the greenhouse. Once again, actual automation is subject to the same limitations as above.

4. HEAT TRANSFER ASSESSMENT

4.1 Temperature fluctuations prediction

The following notation is used in our theoretical development to predict the rate of heat transfer we can expect:

$c_{p,a}$: Specific heat of air (kJ/kg.K)
$c_{p,w}$: Specific heat of water (kJ/kg.K)
ρ_w: Density of water (kg/m^3)
ρ_a: Density of air (kg/m^3)
V_w: Volume of water (m^3)
T_w: Temperature of water (K)
$T_{a,in}$: Air temperature at inlet (K)
$T_{a,out}$: Air temperature at outlet (K)

m_a:	Mass flow rate of air (kg)
U:	Overall heat transfer coefficient ($W/m^2.K$)
A_s:	Surface area (m^2)
ΔT_{lm}:	Log-mean temperature (K)

In the following development, we will establish a relationship that binds the operational parameters of the heat exchanging portion of our greenhouse. For the wording of this description we will assume that air inside the greenhouse is at a higher temperature than the water sitting in the water tank. The physics of the reverse situation are of course equally valid.

For the sake of simplicity, we will assume that no heat is lost to the surroundings through the sidewalls of the water storage tank. The heat is therefore only transferred between the air flowing inside the radiator conduits, approximated as tubes and between the water sitting in the tank that is deemed to have uniform temperature distribution through convective mixing. Given the small temperature variations in and outside of the greenhouse, we will obviously assume all material properties to remain constant. Tube wall conduction will be neglected. Air flowing inside the conduits is assumed to be incompressible, heat gains from frictional dissipation is assumed to be zero.

The amount of heat transfer occurring can be related to the change of the overall heat transfer coefficient of water in the following way.

$$\frac{dU_w}{dt} = \frac{d}{dt}\left(\rho_w V_w c_{v,w} T_w\right) = \rho_w V_w c_{v,w} \frac{d}{dt}\left(T_w(t)\right) = q(t) \tag{1}$$

At the same time, the amount of heat transfer can also be expressed in function of the mass flow rate and specific heat of air flowing inside the tubes.

$$q(t) = \dot{m}_a \, c_{p,a}\left(T_{a,in} - T_{a,out}\right) \tag{2}$$

As we are in presence of internal flow, the same heat transfer rate can also take the following form when expressed in function of the log mean temperature difference.

$$q(t) = UA_s \Delta T_{lm} \tag{3}$$

Where, the log mean temperature difference is given by:

$$\Delta T_{lm} = \frac{\left(T_{a,in} - T_w\right) - \left(T_{a,out} - T_w\right)}{\ln\left(\dfrac{T_{a,in} - T_w}{T_{a,out} - T_w}\right)} = \frac{T_{a,in} - T_{a,out}}{\ln\left(\dfrac{T_{a,in} - T_w}{T_{a,out} - T_w}\right)} \tag{4}$$

Now, substituting (3) and (4) into (2), we obtain:

$$q(t) = \overset{\bullet}{m}_a \, c_{p,a} \left(T_{a,in} - T_{a,out}\right) = UA_s \frac{T_{a,in} - T_{a,out}}{\ln\left(\dfrac{T_{a,in} - T_w}{T_{a,out} - T_w}\right)}$$

Reorganizing, we get the following expression,

$$\ln\left(\frac{T_{a,in} - T_w}{T_{a,out} - T_w}\right) = \frac{UA_s}{\overset{\bullet}{m}_a \, c_{p,a}}$$

Isolating $T_{a,out}$, we obtain an expression that relates the outlet air temperature to the actual water temperature T_w.

$$T_{a,out} = T_w + \left(T_{a,in} - T_w\right) \exp\left(-\frac{UA_s}{\overset{\bullet}{m}_a \, c_{p,a}}\right) \tag{5}$$

Now, we still have to have an expression that will give us the actual water temperature at any give time. Substituting (2) into (5) into (1), we obtain:

$$\rho_w V_w c_{v,w} \frac{d}{dt}(T_w) = \dot{m}_a c_{p,a}\left(T_{a,in} - T_w - (T_{a,in} - T_w)\exp\left(-\frac{UA_s}{\dot{m}_a c_{p,a}}\right)\right)$$

Reorganizing such that we get temperatures at one side and time at the other, we can integrate the expression:

$$\frac{d}{dt}(T_w) = \frac{\dot{m}_a c_{p,a}(T_{a,in} - T_w)}{\rho_w V_w c_{v,w}}\left(1 - \exp\left(-\frac{UA_s}{\dot{m}_a c_{p,a}}\right)\right)$$

$$-\int_{T_{w,0}}^{T_w(t)} \frac{dT_w}{(T_w - T_{a,in})} = \frac{\dot{m}_a c_{p,a}}{\rho_w V_w c_{v,w}}\left(1 - \exp\left(-\frac{UA_s}{\dot{m}_a c_{p,a}}\right)\right)\int_0^t dt$$

$$-\ln\left(\frac{T_w(t) - T_{a,in}}{T_{w,0} - T_{a,in}}\right) = \frac{\dot{m}_a c_{p,a}}{\rho_w V_w c_{v,w}}\left(1 - \exp\left(-\frac{UA_s}{\dot{m}_a c_{p,a}}\right)\right) t$$

Where $T_{w,o}$ is the initial water temperature. Isolating T_w, we finally obtain a relationship for T_w in function of time.

$$T_w(t) = T_{a,in} - (T_{a,in} - T_{w,0})\exp\left(-\frac{\dot{m}_a c_{p,a}}{\rho_w V_w c_{v,w}}\left(1 - \exp\left(-\frac{UA_s}{\dot{m}_a c_{p,a}}\right)\right)t\right) \qquad (6)$$

For any time t, (6) give us the water temperature inside tank and (5) gives us the air temperature at the outlet.

When applied in our situation, we will consider the heat exchanger as collection of tubes where the above relationships apply for each of the tubes. For calculation purposes, the mass flow rate will be that of a single tube, the volume of water will be the total number of tubes divided by the number of tubes. Turbulent flow will be assumed inside the radiator because the entry conditions at the top of the radiator are very likely to trigger turbulent flow. Also, convection heat transfer coefficients will be picked from the literature (Beardmore, 2006).

As we neglect conduction inside the tube wall, U will be calculated as:

$$U = \frac{1}{\frac{1}{h_w} + \frac{1}{h_a}} \tag{7}$$

We will consider two scenarios for illustrational purposes. In the first case, temperature inside the greenhouse is maintained at a constant temperature of 23°C and initial water temperature is at 15°C. This might be representative of a situation where we have a warm day with no heat accumulated inside the storage tank. In the second scenario, we have cold air inside the greenhouse a 15°C but some heat accumulated in the water tank with water at 20°C. These calculations have been carried on on excel spreadsheet and we had the opportunity to explore the sensitivity of some of our parameters.

We used the following data for our calculation:

$c_{p,a}$	1007 J/kgK	$c_{p,w}$	4184 J/kgK
ρ_a	1.16 kg/m^3	ρ_w	1000 kg/m^3
D	0.01 m	V_w	0.85 m^3
$T_{a,in}$	23 °C and 15 °C	T_w	15 °C and 20 °C
L	0.5 m	h_o	1000 W/m^{2}K
Pr	0.707	n	150

As mentioned earlier, the h_o , the initial convection coefficient for water, was picked out of literature. According to Beardmore h_o for free convection of water over various surfaces ranges from 300 to 1700 W/m^2K. The mean value of 1000 W/m^2K was chosen for our purpose. The value n represents the number of tubes forming the 2 radiators.

The cross-sectional area of our tubes is given by

$$A_c = D\pi n = 0.1178m^2$$

This area is about 4 times smaller than the motor inlet area where a velocity of 5m/s was measured using an *Omega Engineering Inc. Thermal Anemometer*. For this reason, a velocity of 1.25m/s will be used in out calculations.

In order to obtain the heat convection coefficient for air, the Re number needs to be calculated to decide whether laminar or turbulent flow prevails inside the tubing.

$$\mathrm{Re} = 4\overset{o}{m}/\pi D\upsilon \qquad \text{with} \qquad \overset{o}{m} = \rho_a v A_c = 1.14E-4kg/m^3$$

Since Re = 785 which is small than 10000, we have laminar flow.

Because the water temperature doesn’t change much, we will use the constant surface temperature relationship for circular tubes in presence of fully developed laminar, namely $Nu_D = h_iD/k = 3.66$. We thus obtain $h_i = 96.3$ W/m^2K. Using equation (7), we obtain U = 87.8 W/m^2K

For the purpose of our calculation, we also need the sleeve area of our tubes which is given by $A_s = L\,\pi D = 0.0157m^2$

The graph below illustrates the above 2 scenarios.

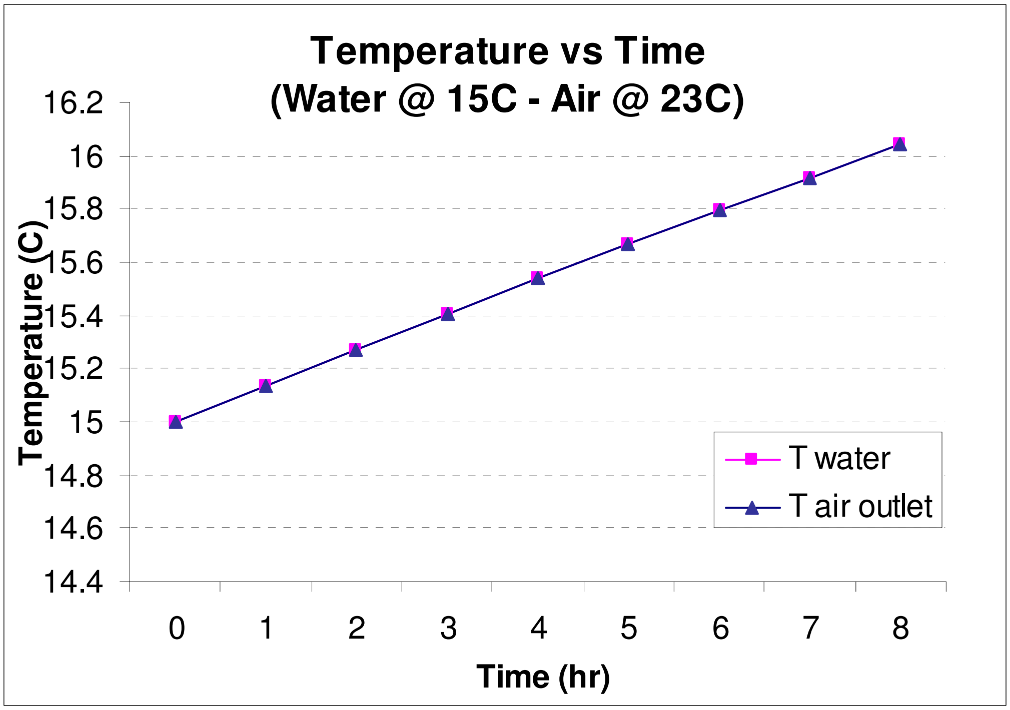


Figure 2: Prediction of temperature change during the day

In the first scenario, we can see that water is gradually warmed up. The temperature rise is however not overwhelming but over several days a pretty substantial delta T can be achieved. As our assumptions work in our favour, we are probably overestimating the actual delta T achieved.

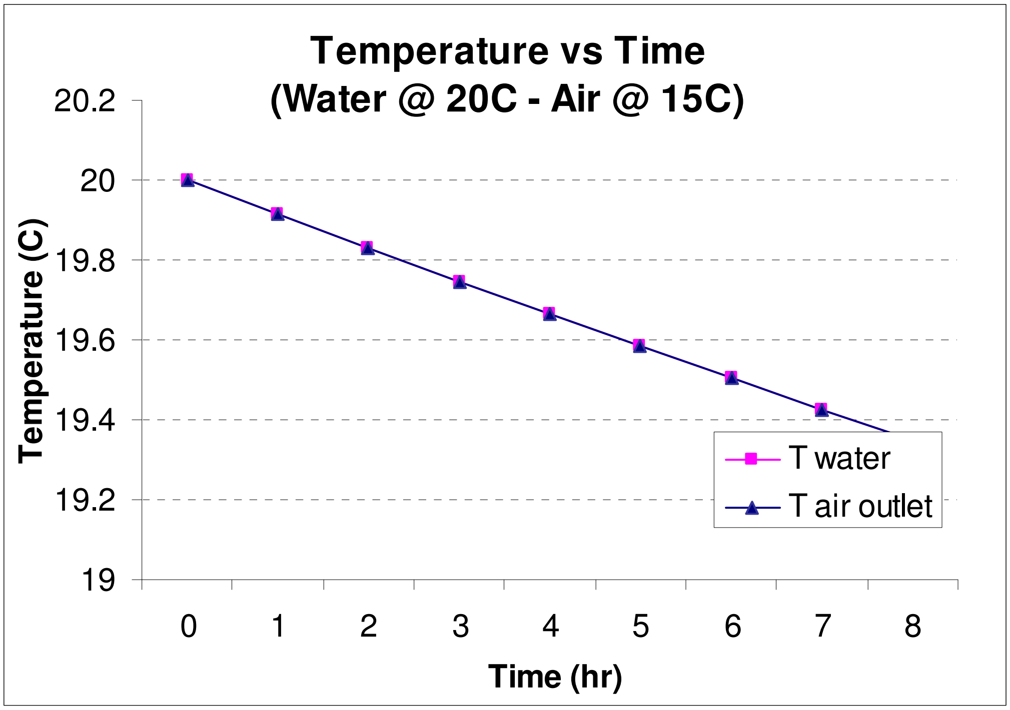


Figure 3: Prediction of temperature change during the night

In the second scenario, we can see a gradual cooling of water while air is heated up. We only loose 0.7°C (by convection to the air passing through the heat exchanger) in the water temperature, so we are not in presence of excessive cooling that would largely offset the heating achieved during the day. Even less cooling could be achieved by reducing the air mass flow rate while still having enough heat transfer taking place to keep the greenhouse at the desired temperature.

4.2 Energy Balance

Variables:

$\dot{E}_{light}$ = radiant energy from lights that is absorbed by the greenhouse($\dot{E}_{radiant,in} - \dot{E}_{radiant,out}$)
$\dot{E}_{\text{water, ambient}}$ = energy that goes from the water tank to the surroundings, through the insulation
$\dot{E}_{\text{greenhouse, ambient}}$ = energy that goes from the greenhouse to the to the surroundings, by conduction and convectio

$$\dot{E}_{in} + \dot{E}_{gen} - \dot{E}_{out} = \dot{E}_{st} \tag{8}$$

The terms in equation (8) are described above in the variables enumeration. The energy coming in the system is the energy absorbed from the light:

$$\dot{E}_{\text{in}} = \dot{E}_{\text{light}} \tag{8a}$$

Also,

$$\dot{E}_{\text{gen}} = 0 \tag{8b}$$

The energy stored is either heat in the greenhouse or heat in the water:

$$\dot{E}_{st} = \Delta E_{\text{greenhouse}} + \Delta E_{\text{water}} \tag{8c}$$

The energy leaving the system is dissipated from the masses of air and water to the surrounding via conductive and convective heat transfer:

$$\dot{E}_{\text{out}} = \dot{E}_{\text{greenhouse, ambient}} + \dot{E}_{\text{water, ambient}} \tag{8d}$$

Assuming the water tank is well insulated:

$$\dot{E}_{\text{water, ambient}} = 0 \tag{8e}$$

By substituting eq.8a, 8b, 8c, 8d and 8e in eq.8 we get:

$$\dot{E}_{\text{light}} + \dot{E}_{\text{ambient, water}} - \dot{E}_{\text{greenhouse, ambient}} = \Delta E_{\text{greenhouse}} + \Delta E_{\text{water}} \tag{9}$$

5. DESIGN STRUCTURE

5.1 Preliminary Design Review

Designing and building the greenhouse were two of the main objectives of this project. One important characteristic of the engineering design process is to generate multiple possibilities and drawings. Many ideas were brought up by the team members in the preliminary phase of the brainstorming. First, we thought we would build ourselves the water tank, the heat exchanger and many more parts. We subsequently thought of a square tank with a copper coil as a heat exchanger, as showed in the figure 1 above. That was our first sketch. However, after couple of conversations with Scott Mantelkow from the Agricultural Engineering Workshop, we decided to reduce the work load and costs (copper being expensive) by simply trying to recycle and reuse as much as possible. Consequently, we opted for used car radiators instead of a customized copper coil. Heat transfer calculations were performed on the possibilities of such a heat transfer apparatus. From those heat transfer calculations, we concluded that there was sufficient heat transferred from the air to the water to go ahead with the project. As a result, many questions were brought up concerning the location of the radiators and the fluid flowing inside the radiator. In the case of the fluids, we had to play with air and water as heat exchange fluids, since we are in presence of hot air inside the greenhouse and water is easily available and has a great heat storage capacity. Our preliminary idea was to use still water as a heat sink and blowing air through the radiators, which would be placed inside the tank. This plan was fulfilling the low energy input and low complexity criteria.

Later on, we thought about a design which would have the radiators inside the greenhouse. Hot air could be blown through the radiators with water flowing inside it. Heated water from the radiators would go inside the water tank and water to water heat exchange would hence occur. Blowing air through radiators with water flowing through would probably demand more energy, given that water is more viscous. Therefore, this idea was discarded, even though we felt this method would have been more efficient heat transfer wise. When we had a coarse idea of the structure and the different parts of the greenhouse, we next had to construct them and sketch *Computer Aided Drawings (Design)* in order to go forward methodically. In the subsequent section is found a description of the material and equipment used in the implementation of the various parts of the greenhouse are described.

5.2 Actual Design

The actual design of the greenhouse is a hybrid of engineering and proactive tinkering. Time and costs constraints pushed us to come out with this final design. Here we describe the system and its different components. A motor with a fan will blow the hot air from the green house inside tubes that will conduct the air inside two radiators fixed inside the water tank. The two radiators, submerged in water, will generate, by free convection, transfer of the heat to the water mass. If condensation of the hot air occurs inside the radiators, it is conveyed outside the tank by gravity inside plastics tubes. The cool dry air is blown back into the greenhouse.

5.3 Materials & Equipment

The materials and equipment used for the implementation of the greenhouse were chosen according to our ultimate objective, being both inexpensive and environmentally friendly. Some of the equipment was purchased from the hardware store, some was directly borrowed from the McGill's Agricultural Engineering Workshop on Macdonald Campus, and some was cleverly taken from scrap yards and dumps. In the next paragraphs, we generated a synthesized version of the materials and equipment list. A more exhaustive description of materials and equipment can be consulted from the appendix. Here are some of the more important items:

- Steel water (oil) tank
- Plastic pipes (various sizes)
- Radiators
- Steel bars
- Plexiglas
- Linoleum
- Motor & casing
- Fan
- Mineral wool, Polyurethane, silicone, hot glue
- T-fittings, washers, knobs, nuts, bolts, screws, collars

5.3.1 Greenhouse Components

Water tank

The water tank is a disaffected oil tank given by a heating supply retailer. Its nominal volume was 900 litres and once in operation we used 850 litres of water in it. It was carefully washed and water tightened by welding metal pieces and adding adhesive silicone or hot glue. The tank was insulated with air duct mineral wool insulation salvaged from the MacDonald Library renovation and tightly attached with duct tape, which is not very aesthetic, but rather efficient. The tank was bolted to a wooden pallet, in order to facilitate its movement once it would be filled with water. The screws were sealed with a screw sealer and a piece of bicycle rubber was sandwiched between the tank and the washer to inhibit leaking.

Steel bars

The steel was taken from the workshop leftovers. Note that all the parts that were implemented by the team members were done by using the workshop machinery and tools, under the supervision of Mr. Scott Mantelkow and Dr. Samson Sotocinal. To build the bars, we had to calculate the inclination of the radiators for the condensation system. The condensed air in the radiators would travel down into tubes and be evacuated outside the tank. A simple calculation with similar triangles and Pythagoras theorem was used in that case.

Radiators

The radiators were purchased in a automotive scrap yard. They are both *Hyundai Excel 1991* radiators. In order to enhance the heat transfer, the two heat exchangers were washed using *CLR*. The radiators were mounted on custom made steel bars. All dimensions and sketches of the custom made parts are available in appendix.

Pipes

The pipes are plastic tubes bought at the hardware store. Various sizes are designated for various purposes. The bigger 2 in. pipes are for the air inlet. The medium 1.25 in. is for the air outlet. The smaller 0.5 in. is for the condensation removal system. The pipes were attached with collars of appropriate size taken from the shop.

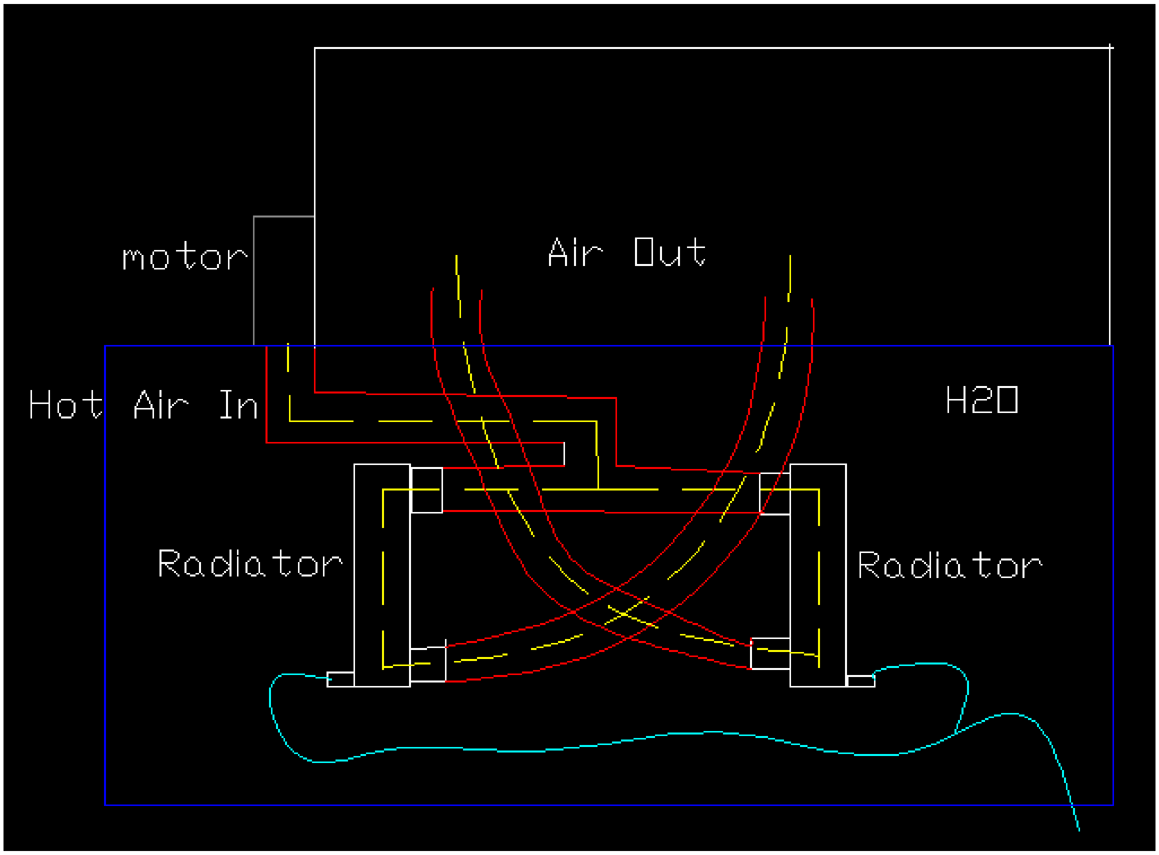


Figure 5. Side view of greenhouse

Motor, motor casing & fan

The motor is a real piece of art. It is a refurbished motor taken from different parts in the shop. We had to cut electrical wires and fix them to the motor. The squirrel cage type rotor also needed to be modified in order to fit into the motor's shaft. All the different parts were assembled and fixed on a specially built wooden plaque, which was also used to fix the motor assembly to the greenhouse with the help of customized steel "L" ears.

Glazing

The glazing for the greenhouse came from the Agricultural Engineering Workshop as well. We used a 4 ft by 5 ft sheet of Plexiglas, which is quite smaller than what we expected, but considering these plastic are somewhat expensive, and the project focuses primarily on heat exchange, we figured buying any more Plexiglas would have been frivolous. The sides of the glazing were made of corrugated white plastic, since no more Plexiglas was available. The glazing and the motor were sealed with adhesive silicone. A blanket of black plastic fabric was laid down at the bottom of the greenhouse in order to absorb heat. It also emulates soil that we would normally encounter in a real life scenario.

Top cover

The top cover of the water tank is made of an abandoned piece of press wood found at the workshop. It was bolted in place in the tank at the four corners from the inside. The bolts were welded to the tank. The cover is removable permitting to work on the radiators and the piping system. The Plexiglas was fixed to the cover by nailing wooden strips along the edges of the cover and bending the Plexiglas in a semi circular manner to fit in the strips.

5.3.2 Greenhouse Assembly

The greenhouse was assembled at the shop. It was mounted on a pallet which was mounted on a jigger in order to be able to move the tank around for testing and fixing. It is also important to note that we used lots of different screws, nuts, washers, knob, tap etc. The part drawings are available in the appendix, the drawing below gives an idea of the greenhouse in the exploded view. To see a picture of the real greenhouse refer to the appendices.

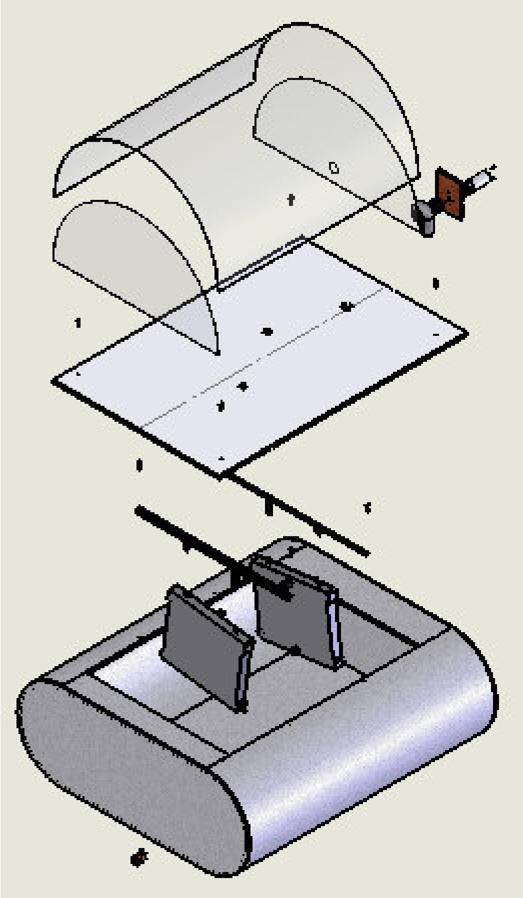


Figure 8. Greenhouse Exploded View

5.4 Computer Aided Design

Once the final design and components are determined, we could start building the greenhouse. We perform multiple drawings with the help of a CAD software, *Solidworks*©, in order to visualize better the structure as we were building it. We hence had to measure all parts constituting the greenhouse in order to design on the computer. We designed the different greenhouse parts after we got them and built them. A true engineering approach would have been to design the parts with all specifications and used them in the assembly. Nevertheless, all the components and assemblies can be viewed in the appendix. Those drawings could be used by anybody who wished to build a similar greenhouse. Below is an example of the drawing of the motor assembly.

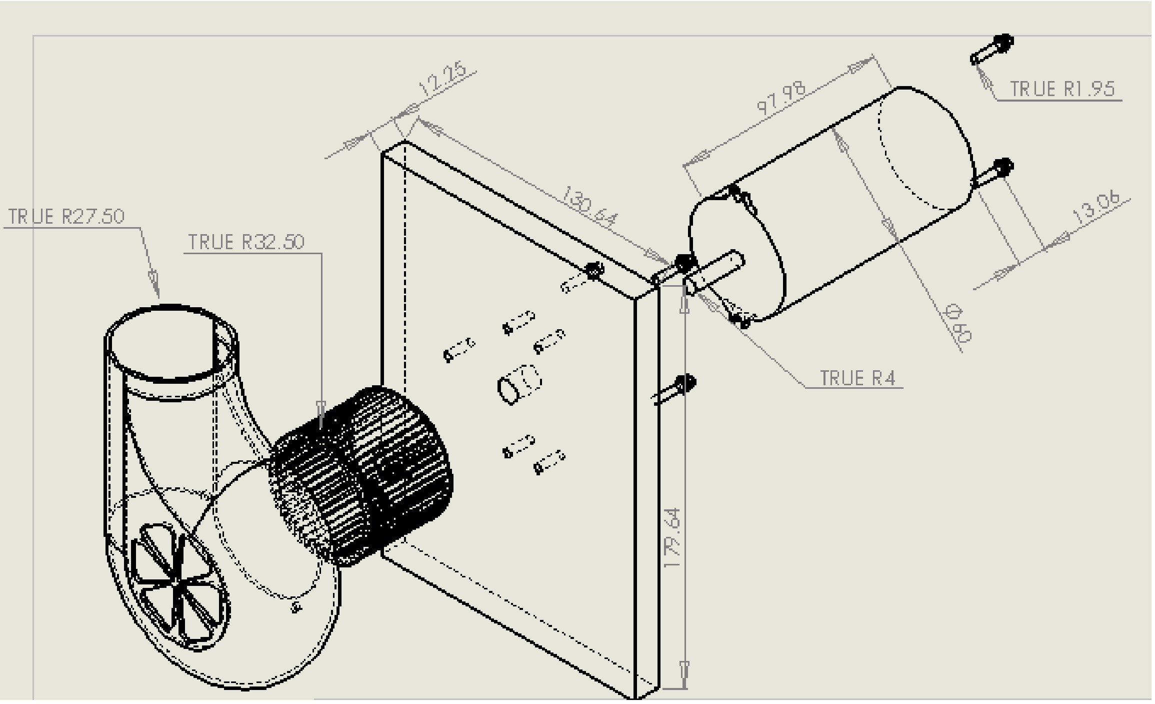


Figure 9. Motor Assembly drawing

5.5 Testing Procedure

The mini-greenhouse has been tested in the Agricultural Engineering Workshop. Three series of tests were run in order to understand its behaviour. The environment inside where the tests were done was a hangar, which was lighted during 8.5 hours per day and dark during the other 15.5 hours. The light intensity was not exactly measured, but it seemed to sufficiently replicate a spring sunny day. The temperature reached a maximum of 24°C during the day and a minimum of 5°C during the night, for an average temperature of 14°C. The temperature of the water in the tank had negligible fluctuations over a day if not disturbed since the water tank was quite well insulated. Due to time and budget constraints, no data was collected in order to assess the moisture removal potential of our apparatus.

5.5.1 Midday equilibrium temperature tests

The first two tests were simple ones and only involved the use of a simple 4-inch probe thermometer. The ambient air, greenhouse, water and radiator outlet temperatures were measured before and after the fan was turned on, as well as after the system reached short term equilibrium. This was done at 2:00pm, when the room temperature is at its daily peak.

5.5.2 Two-day temperature fluctuations test, with forced heat exchange

This test was run during two full days with 8.5 hours of lighting per day. Ambient air, heat exchanger outlet and greenhouse air temperatures were measured at 5 minutes intervals using a SM325 Dickson data logger. The water temperature was measured twice a day, using a probe thermometer, when the light was turned on and turned off. The fan was turned on during the lighting period, being triggered by a timer. Forced heat exchange was therefore happening during 8.5 hours per day. During the night, passive heat transfer was happening between the mass of water and the air inside the greenhouse. The test lasted for 48 hours.

6. RESULTS

6.1 Midday temperature equilibrium test

6.1.1 When apparent steady-state is reached

Given:

Measured:

- $T_{ambient}$ = 24°C
- T_{outlet} = 12°C
- $T_{greenhouse}$ = 23.5°C
- T_{water} = 12°C
- V_{inlet} = 5m/s (measured with a pitot tube)
- A_{inlet} = $0.00283m^2$
- V_w = $0.85m^3$

From tables (Incropera, 2004):

- ρ_{air} = 1.1614kg/m^3, at 18°C
- $C_{p,air}$ = 1.007kJ/(kg*K), at 18°C
- $C_{p,water}$ = 4189kJ/(kg*K), at 12°C

Find active heat transfer rate q, from greenhouse air to water.

Assumptions:

- No passive heat transfer between greenhouse air and water.
- Water tank perfectly insulated.
- Neglect heat gain from viscous friction

Analysis:

$$\Delta E_{water} = q = \dot{m} C_{p,air} (T_{inlet} - T_{outlet}) = VA\rho C_{p,air} (T_{greenhouse} - T_{outlet})$$
$$\Delta E_{water} = q = 5m/s * 0.00283m^2 * 1.1614kg/m^3 * 1.007KJ/(kg*K) * (23.5°C - 12°C) = 190W$$

This energy stored in the water tank, rises the temperature of water in the tank. The diminishing difference in temperature between air and water will gradually reduce this heat transfer rate during the day, changing the greenhouse air and water tank temperatures at variable rates.

The heat transfer rate calculated above is energy that is removed from the greenhouse air. This energy is mostly supplied by the incoming radiation from light, since the ambient temperature is only 0.5°C away from the greenhouse air temperature, assuring us that conduction and convection heat transfer through the glazing can be considered as non existent.

We can therefore assert that, from equation (9):

$$\dot{E}_{\text{light}} + \dot{E}_{\text{ambient, water}} - \dot{E}_{\text{greenhouse, ambient}} = \Delta E_{\text{greenhouse}} + \Delta E_{\text{water}}$$

$$\Delta E_{\text{greenhouse}} = 0$$

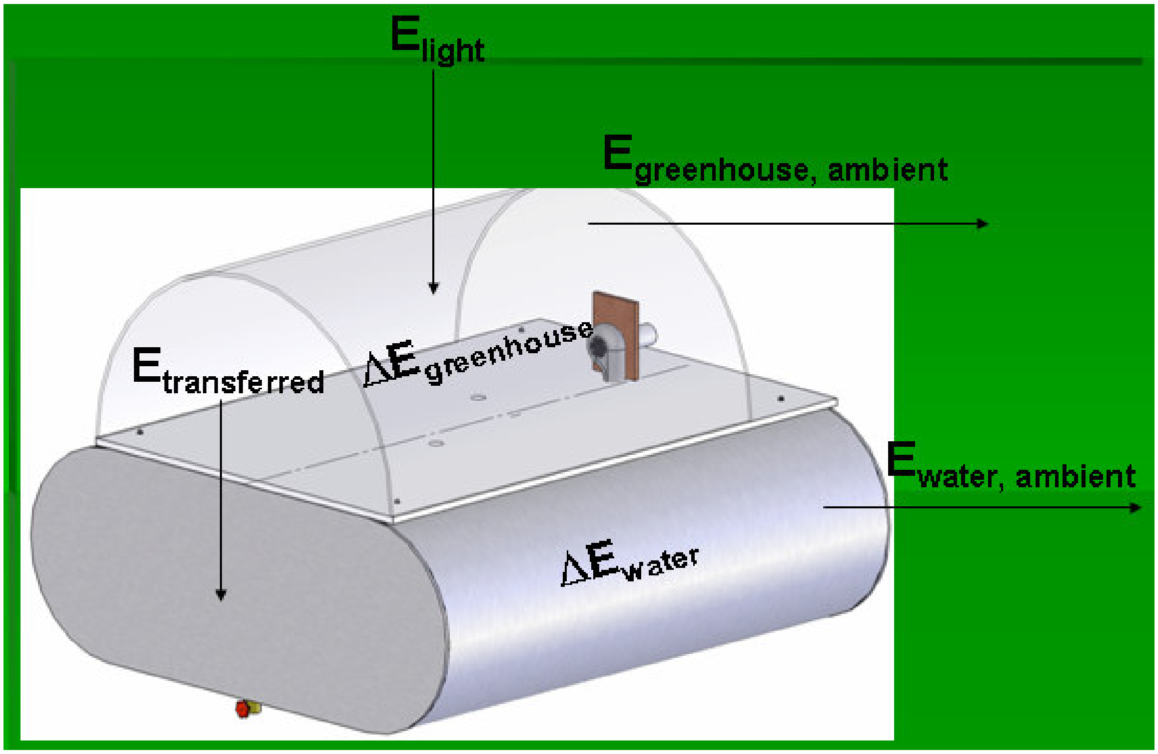
$$\dot{E}_{\text{ambient, water}} = 0$$

$$\dot{E}_{\text{greenhouse, ambient}}$$

$$\dot{E}_{\text{light}} = \Delta E_{\text{greenhouse}}$$

$$\dot{E}_{\text{light}} = 190W$$

Figure 10. Energy balance of the greenhouse



6.1.2 Before fan is turned on

- T_{ambient} = 24°C
- T_{water} = 12°C
- $T_{\text{greehnouse}}$ = 32°C

Since the system is at an apparent steady state during this experiment and water temperature changes very slowly, we can assume that:

$$\Delta\dot{E}_{\text{greenhouse}} = 0$$
$$\Delta\dot{E}_{\text{water}} = 0$$
$$\dot{E}_{\text{ambient, water}} = 0$$

Therefore, from eq.9, we get:

$$\dot{E}_{\text{light}} = \dot{E}_{\text{greenhouse, ambient}} = 190W$$

R_{tot} can be defined as the sum of the resistances due to heat loss from the air of the greenhouse to the surroundings, through the glazing:

$$\begin{aligned} R_{\text{tot}} &= R_{\text{convection, in}} + R_{\text{conduction, glazing}} + R_{\text{convection, outside}} \\ R_{\text{tot}} &= \Delta T / q, \text{ where } q = \dot{E}_{\text{greenhouse, ambient}} \\ R_{\text{tot}} &= (32°C - 24°C) / 190W = 0.0631K / W \end{aligned}$$

6.2 Two-day temperature fluctuations test, with forced heat exchange

According to the original plans, a data logger (SmartReader1, ACR system inc.) has been set up to take the temperature measurements at regular time intervals. Manual measurements have also been taken during the mornings and late afternoons in order to validate the data from the logger. After the 48 hours measuring session, it turned out that the data logger failed to record any temperature information so we have defaulted back to our manual measurement with a cooking thermometer to assess the heat transfer taking place inside the greenhouse. This detail is really unfortunate however time limitations did not allow us to proceed with a second data logging session.

The following table contains data from out manual temperature measurements.

Time(h)	$T_{ambient}$(°C)	T_{water}(°C)	$T_{greenhouse}$(°C)	T_{outlet}(°C)
0 (morning)	21	14	23	14
8.5 (afternoon)	24	16	24	16.5
24 (morning)	20	16	24	16
32.5 (afternoon)	24	18	25	18.5
48 (morning)	21	18	24	18

Table 1. Temperature measurements during the 48h test period

It appears from the table above that the greenhouse is working according to its intended use, water is heated up and air coming out from the outlet cooled down. The actual delta T achieved in the first 8 hour period is actually higher than what we predicted in out theoretical model. This could be explained by the fact that the water is not only heated with the help of air circulating in the radiators but also must have gained considerable amount of heat from the surroundings where the ambient temperature was at 21°C. As the fans were only working during the day, we did not compare the cooling process with the one simulated. However, we can pretty much see that nearly no heat got lost to the surroundings during night which can be explained by both not so cold ambient temperatures inside the workshop as well as by benefit of the insulation around the water tank.

The following figure summarizes the simulated and the observed water temperature changes. The outlet air temperature has been removed from the graph for the sake for better readability as it follows closely the water temperature.

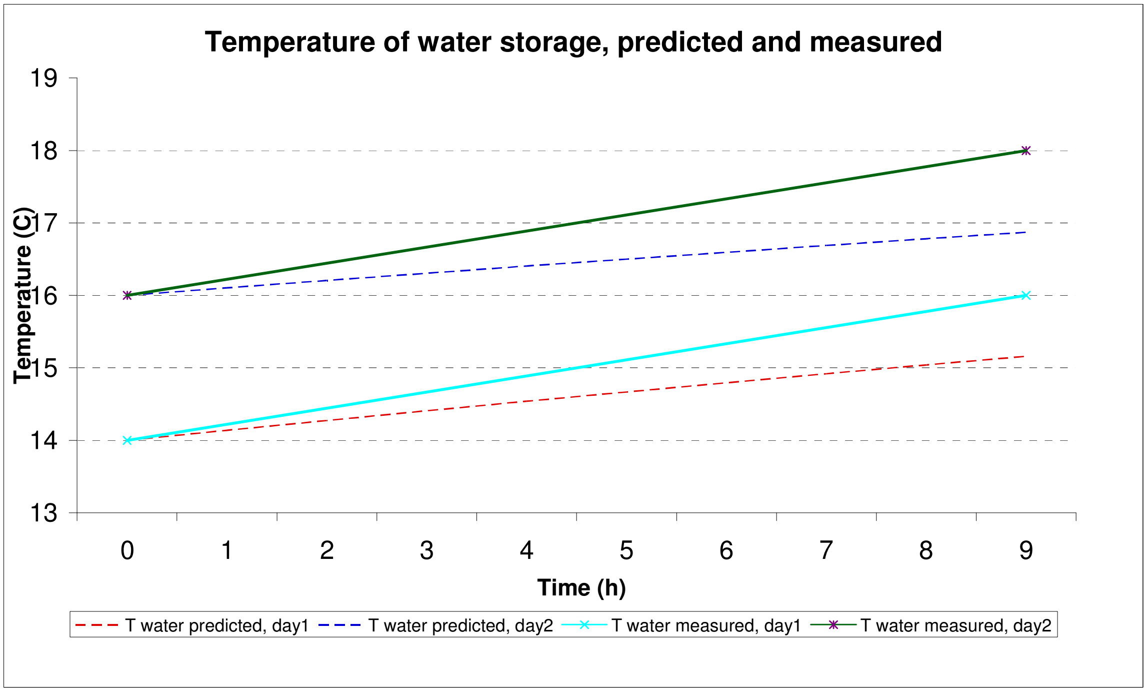


Figure 10: Comparison of predicted versus actual water temperatures

We can see that the actual temperature change is greater than the value we have simulated. The predicted values are underestimated, but the general trend is the same. Possible causes are discussed in the following section.

7. DISCUSSION

7.1 Possibilities for efficient energy use

Our energy balance is potentially oversimplified. We could have integrated into it several more aspects relevant to greenhouse production and efficient energy use.

One of them is the energy dissipated by the fan motor, which was outside our greenhouse. In an efficient system, it should be inside the greenhouse so that any energy invested in running it ends up as usable heat, which comes from either the motor or the frictions losses from the air it displaces. Since all energy used to run the motor ends up as heat, the costs related to this system are costs of ownership and maintenance.

Another component worth noting is the removal of moisture, which was at low levels in our experiment since we did not include any plants. At 85% of relative humidity and a greenhouse temperature of 32°C, condensation will occur when the air drops to 29°C. This is very likely to happen when the water tank temperature is below that, because the temperature of the radiator at the interface of the flow of air is shown in our experiment to be very close to that of water. However, the amount of condensation in the heat exchanger is shown to be negligible, in depth calculations and proper experimentation would be needed in order to assess it.

Moisture removal is accompanied by latent heat release, which can release as much as one third of the heat removed from moisture (Campen & Bot, 2002). Energy from latent heat of vaporization could therefore be considered in an energy balance and it is advantageous to us since it is usually lost with ventilation.

The heat loss through the tank walls was assumed to be zero and it in fact showed to be quite close to this in reality: during the 15.5 hours that the night lasted the water tank showed no measurable decline in temperature. To increase the insulation of the system investing in high performance greenhouse glazing should give better results than acrylic panes.

Automation of the heat transfer process, which we initially intended to implement, would undoubtedly provide room for more intelligent and efficient energy budget management. The greenhouse temperature could therefore match more accurately the seedling needs and heating could be automated so as to increase the yield/energy ratio.

Energy losses from ventilation are expensive to producers, and means to reduce them need some financial input. An economic analysis of the benefits of a more energy efficient greenhouse is not the purpose here but it is certainly worth considering before investing in energy saving technologies.

7.2 Shortcomings, assumptions and simplifications

The assumptions in our theoretical development were probably too idealist. First, the constant temperature inside the greenhouse probably cannot be sustained simply through solar energy input when cooling is taking place by circulating air through the heat exchangers. As we have seen both in the simulation and actual measurements, the air temperature at the outlet is almost identical to the water temperature inside the tank. The mixing of outlet air with the air of the greenhouse inevitably changes the temperature of the greenhouse impacting therefore the inlet temperature. For this reason constant inlet temperature could not be reasonably assumed.

In our testing setup, the solar radiation was replaced by radiating heating elements mounted to the ceiling of the Agricultural Engineering Workshop. To what extent does this radiating heating effectively emulate solar radiation is unknown to us. Furthermore, the Plexiglas sheet we used in lieu of proper glazing has no IR treatment on the inside so heat isn't trapped inside our prototype greenhouse to the same extent as it would be the case in a more sophisticated design.

The assumption that no heat would be lost to or gained from the surroundings is obviously not valid either. The insulation that we used had an unknown R value as it was recycled from construction scrap materials. It was cut to shape to the best of our ability and fixed to the tank by means of duct tape. The underside of the tank being fixed to a wooden pallet received foam insulation where bare metal was still accessible. Even though the finished overall insulation was the best we could achieve given the means available to us, better results could certainly be reached if carried out in a professional way. The actual heat loss or gain occurring to the surroundings was not quantified as we did not focus on the heat transfer from the surroundings.

The heat exchangers used in the design were automotive radiators developed to circulate a liquid inside the radiator and have air flowing across in a forced fashion. The finned surface is exposed to the outside in order to maximize heat exchange between the air and the radiator. In our application the finned surface became exposed to the water whereas the air was in contact with the probably smooth surface of the inside of the radiator. This alone is a major limitation to the amount of heat transfer occurring in our application. If we add the fact that we used previously enjoyed radiators and the inside of the tubes were probably coated with calcium remaining even though we flushed it with CLR, the heat transfer coefficient could have been nonetheless reduced.

The motor-rotor combination seemed to be very powerful in the beginning, even though we feared this to have too much air flow. However the resistance introduced by the radiator and the different fittings and reducers used to hook the system together reduced our effective flow beyond our worst fears. This problem has two aspects to it: the energy dissipation though viscous friction eventually ends up as heat inside the greenhouse and lower mass flow rate actually reduced the amount of heat transfer that could possibly take place.

7.3 Design improvements in the context of actual design state

If more time was available to us, the next step in the engineering design process would be the redesigning step. As far as heat transfer and storage is concerned, the project can be qualified a success. We have achieved heat storage but not without a certain number of shortcomings. The motor we used in our design was rather powerful and very noisy. The monetary expense of operating such a powerful motor should certainly be quantified. Through the lack of proper instrumentation we have also operated the motor during the entire daytime. The question also remains whether on-demand (versus continuous) operation of the motor would have achieved similar results. This also ties in with the need of more rigorous testing environment. It is a real pity that the data logging didn't deliver the expected results in time.

We also feel that two areas where we could bring improvements are the resistance in tubing and the heat transfer efficiency between the air and the heat exchanger. Losses in the air flow could be optimized though the use of custom made fittings and properly sized tubing. Tubing and fittings that we used were chosen of what were available in walk-in stores. At a small additional expense, properly sized tubing and fittings could probably be ordered from specialized catalogues. The heat exchangers from specialized brochures would however be prohibitively expensive so going this route is not possible for us. One improvement that was invoked by our team was to mount the automotive radiators transversely in a box and blow air across them while water would be circulated inside the radiators. This would be a better way of accommodating the use of automotive radiators where most of the finned area is exposed to the outside of the exchanger. Of course, we must also factor in the expense of added complexity and the need of pumping water in addition to pumping air. The economics of the design would need further investigation. The energy requirements of such a design might not counterbalance the energy saved and manufacturing process would also become more complex and expensive. Later regular maintenance would also increase in price. A custom designed heat exchanger would still be the best route to go in terms of simplicity and efficiency of the design even if more expensive in terms of initial investment. However such a heat exchanger is beyond our reach in the context of our undergraduate design project.

We have heavily insisted on automation in our design proposal. At the actual state of affairs we do have working prototype but a possible redesign would probably improve things a lot. A newer prototype would however have possibly different requirements in terms of automation. Testing material was made available to us by Dr. Samson Sotocinal so any other testing and monitoring device was not necessary at this stage. We nevertheless asked the expert opinion of Dr. Ning Wang in terms of automation and control. Measuring and logging temperature and controlling a fan would have been at our reach in terms of technical complexity if timing had permitted to implement it. On the other hand, moisture level monitoring was deemed to be outside of our level of expertise by Dr. Wang.

8. CONCLUSION

With tremendous help and insight from Scott Mantelkow we succeeded in achieving our goal despite our limited financial resources. We gained a lot of knowledge and good reflexes in managing a project on a tight budget which will certainly pay its dividends in our professional career. We also cannot help but felicitate ourselves for our endeavour to provide a heat storage alternative for greenhouses while at the same time offering a viable moisture removal solution as a bonus. This special combination of features makes our greenhouse innovative and revolutionary per se. Our ideas were also very well received by our professional acquaintances in the greenhouse industry.

Some of the problems encountered during the realization of this project can be brought back to financial limitations forcing us to use what was available instead of what would have been ideal for the given situation. In the context of an undergraduate design course, these financial limitations are not likely to be easily removed, but we feel some sensible improvements could still be carried out in the same spirit of limited resources. The need for less energy requirement, more efficient heat transfer and good instrumentation are certainly among the top priorities. We certainly feel that taking the greenhouse to the next level would qualify as a good senior design project for students in our department.

8. BIBLIOGRAPHY

Ahmet Kürklü, S. B., Burhan Özkan (2002). "A study on the solar energy storing rock-bed to heat a polyethylene tunnel type greenhouse." Renewable Energy **28**: 683-697.

University of Arizona (2002). "Greenhouse energy conservation and alternatives." Retrieved march 3rd, 2006, from ag.arizona.edu/CEAC/basics/notes/chapter13.pdf.

Anonymous (1978) Joseph Orr's fabulous "mud heat-storage" solar greenhouse. Mother Earth News. http://www.motherearthnews.com/library/1978_May_June/Joseph_Orr_s_Fabulous__Mud_Heat_Storage__Solar_Greenhouse, site consulted on 23/02/06.

Basçetinçelik, H. H. Ö. A. (2003). "Experimental evaluation of energy and exergy efficiency of a seasonal latent heat storage system for greenhouse heating." Fuel and Energy Abstracts **46**(6): 379-379.

Beardmore, Roy. RoyMech, 2006. Website, available at www.roymech.co.uk/Related/Thermo.html

Bernier, H. (1987). Energy conservation using a soil heat exchanger-storage system in a commercial type greenhouse. Department of Agricultural Engineering. Montreal, McGill University. **Master of science:** 145 pages.

Campen, J. B. and G. P. A. Bot (2002). "Dehumidification in Greenhouses by Condensation on Finned Pipes." Biosystems Engineering **82**(2): 177-185.

Campen, J. B., G. P. A. Bot, et al. (2003). "Dehumidification of Greenhouses at Northern Latitudes." Biosystems Engineering **86**(4): 487-493.

de Halleux, D. and L. Gauthier (1998). "Energy Consumption Due to Dehumidification of

Greenhouses under Northern Latitudes." Journal of Agricultural Engineering Research **69**(1): 35-42.

Incropera, F. P. and D. P. DeWitt (1996). Fundamentals of heat and Mass Transfer, 4th ed. John Wiley & Sons. 886p.

Ménard, O. (1991). A solar climated control system using a water film flow to conserve energy in greenhouses. Department of Agricultural Engineering. Montréal, McGill University. **Master of Science:** 112 pages.

Rodriguez, M. R., M. D. Fernandez, et al. (2004). "Electrical Wire Heating in Sand Substrates: Influence of Depth and Spacing on Power per Unit Length." Biosystems Engineering **89**(2): 187-195.

Sanford, S. (2006). "Reducing natural gas / propane use for greenhouse space heating." Retrieved march 12th, 2006, from www.uwex.edu/ces/ag/issues/naturalgas/documents/Reducing_Natural_Gas_-_Gree.pdf.

10. APPENDICES

Appendix A: Costs

Estimated cost of project

Item	**Price***	**Source**
Sensors (light, temperature, moisture) 6 @ 35$ each	210$	Parallax
Microprocessor	80$	Parallax
USB programming board	110$	Parallax
2 Fans	100$	XPCgear
Glazing, 2-layer polycarbonate	200$	Solexx
Heating cable, 130W	80$	ACF Greenhouses
Wiring	20$	Addison
Structure (steel)	80$	Rona
Insulation (polyurethane)	20$	Rona
Wheels	20$	Rona
Coil (copper, ½ inch, 50 feet)	100$	Plumbing World
Thermostat	50$	Rona
Thermal blanket	40$	Advanced Greenhouses
Water tank lining	40$	Rona
Capillary mat	50$	Rona
196 man hours (50$/hour)	9800$	
Total	**11000$**	

*Prices include shipping and taxes and are rounded up to the ten above

Actual cost of project

Item	Price*	Source
Oil tank	Free	Shop
Radiators (2)	70 $	Le Pere de la Scrape
Radiator Steel Bars (2)	Free	Shop
2 in. tubing x 2 ft	10$	RONA
1 in. tubing x 5 ft	10$	RONA
1 1/4 in. tubing x 5 ft	10$	RONA
Collars 2 in. (4)	12$	RONA
½ in. tubing x 6 ft	10$	RONA
Collars (6)	Free	Shop
Nuts (20)	Free	Shop
Screws (20)	Free	Shop
Washers (20)	Free	Shop
Silicone	6$	CDN TIRE
Hot glue	Free	Shop
Tap + Knob	10$	RONA
T-fittings copper	12$	RONA
T-fittings plastic	5$	RONA
Top cover press wood	Free	Shop
Nails(20)	Free	Shop
Wood	Free	Shop
Polyurethane(2)	20$	RENO DEPOT
197 hr * 50$/hr	9850$	
Total	**10 025$**	

*Prices include shipping and taxes and are rounded up to the ten above

Appendix B: Work Schedules

Estimated work schedule

	-Dimensions of greenhouse	2h
PHASE I	-Structural design	6h
	-Glazing design	3h
	-Heat exchanger design	5h
April 2006	-Secondary heat source design	2h
	-Evaluation of condensation potential	3h
	-Types of sensors and fans needed	4h
	-Components for the control system	3h
	-Watering system design	3h
	-List of materials needed	2h
May 2006	-Finding materials	20h
	-Making a budget	3h
	-Buying and gathering materials	6h
June 2006	-Elaborating the algorithms and programming	15h
July 2006	-Break	
PHASE II	-Build the structure of the water tank	6h
August 2006	-Insulating and lining the water tank	5h
September 2006	-Making the coil and condensation container	5h
	-Installing the coil and closing the tank	4h
	-Adding a heating cable and sand	3h
	-Adding a capillary mat	3h
	-Making the glazing	8h
	-Installing the fans, thermocouples, humidity sensors and microprocessor.	5h
	-Finalizing the assembly	
		8h
October 2006	-Testing and calibrating the mini-greenhouse	8h
	-Putting the mini-greenhouse in operation for a long term test	5h
	-Gathering data from tests	
	-Interpreting results	4h
		10h
November 2006	-Making needed changes to the mini-greenhouse	10h
	-Writing report	
		30h
December 2006	-Finalizing the report	20h
	Total	**196h**

Actual work schedule

PHASE I April 2006	-Dimensions of greenhouse -Structural design -List of materials needed -Proposal report	2h 6h 3h 10h
July 2006	-Break	
PHASE II September 2006	-Finding materials -Making a budget -Buying and gathering materials -Build the structure of the water tank -Insulating and lining the water tank	20h 3h 6h 12h 5h
October 2006	-Making the radiators bars and condensation container -Installing the radiators and closing the tank -Making the glazing -Building and fixing of motor -Finalizing the assembly	5h 4h 2h 2h 8h
November	-Installing and testing the tubing system -Testing and calibrating the mini-greenhouse -Gathering data from tests -Interpreting results	4h 8h 48h 4h
PHASE III December 2006	-Writing report -Making needed changes to the mini-greenhouse -Finalizing report -Automation of the greenhouse (Not done)	30h 10h 10h 0h
	Total	**207h**

Appendix C: Water tank full

Appendix D: Motor and fan

Appendix E: CAD Drawings