McGill University

Engineering Design 3
Project Report
Optimization of Heat Extraction and Transfer from Compost to Greenhouse

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Producing and eating locally grown food year round is an ideal model to strive towards. Reducing imports of food can provide natural health and environmental benefits. Unfortunately, the energy required to produce foods locally in the cold season using conventional greenhouse technologies is resource intensive, polluting and expensive. Reducing or eliminating the use of fossil fuels for climate control can be achieved with a hydronic biothermal system. Harnessing heat from the thermophilic stage of composting using water as a means of heat transfer and space heating a greenhouse can facilitate the growing of crops in cold climates. The design will help to understand compost as an alternative source of energy.

Table of Contents

List of Tables and Figures

Figures

Tables

Introduction

Global food security is very important and providing enough food for everyone is a crucial aspect of human survival. According to the Food and Agriculture Organisation of the United Nations (FAO, 2011), there was one billion unnourished people in 2011, which is about one seventh of the current global population. This phenomenon is explained by the fact that human population and food demand grow exponentially whereas the food supply is a linear model. Therefore, even in smaller scale operations, it is important to make the process of food production more efficient in order to account for this rise in food demand.

Greenhouse Concept

Greenhouses have proved to be an efficient practice used to optimize vegetable production yields. Greenhouses are present all over the world and in the 2011 version of the World Greenhouse Vegetable Production Statistics, it was estimated that the total worldwide area of greenhouse vegetable production was 402 981 hectares (WGVPS, 2011). The major players are Spain, the Netherlands and Mexico in descending order. Growing in greenhouses provides optimal conditions and therefore production can be done on a year-round basis, extending the growing season of produce. Natural of physical factors can influence the environment in a greenhouse. Natural factors arise from the velocity, humidity and temperature of the air, the daily amount of natural sunlight and other outside conditions. Physical factors depend on the specific size, geometry and material of the greenhouse and on the equipment and plants grown under its roof. With this being said, greenhouses usually don’t require a lot of energy input, but in colder climates such as in Canada, additional inputs of energy are needed. These additional inputs of energy can be costly and in most cases are obtained from the burning of fossil fuels. It is important to be able to provide an efficient and renewable source of energy to the greenhouses so that the benefits are not obtained at the expense of burning fossil fuels.

Composting Process

Composting is defined as the "biological decomposition and stabilization of organic substrates under condition which allow development of thermophilic temperature as a result of biologically produced heat, with final product sufficiently stable for storage and application to land". It is a biological decomposition of biodegradable wastes which mainly produce carbon-rich and nitrogen-rich organic matters, carbon dioxide, water, and heat. The process occurs at high temperatures and we are interested in reusing the heat that this reaction produces.

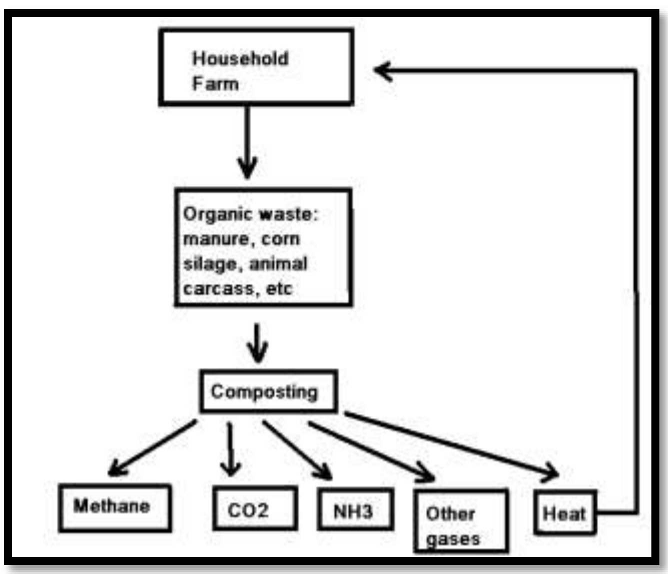


Figure 1: Composting
(Chongrak Polprasert. "Chapter 3: Composting", *Organic Waste Recycling, Technology and Management*, *3rd edition.* @2007 IWA Publishing.)

Conventionally, composting consists of four major microbiological phases (in Figure 2): latent phase, growth phase (or mesophilic phase), thermophilic phase, and maturation phase (cooling). It is during the thermophilic phase that the temperature reaches the highest level, which is theoretically about 60 ^{o} C.

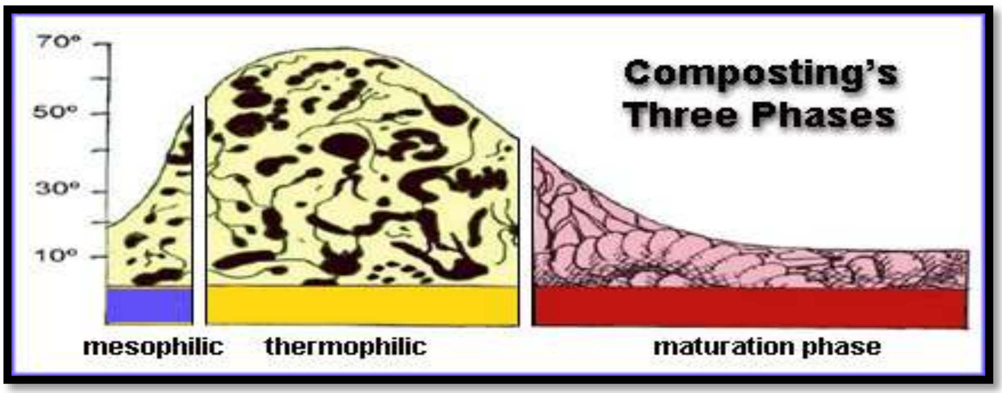
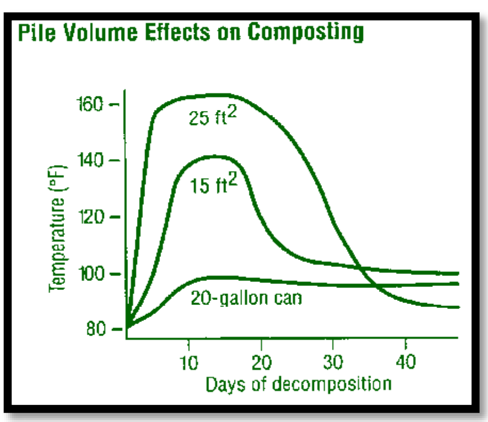
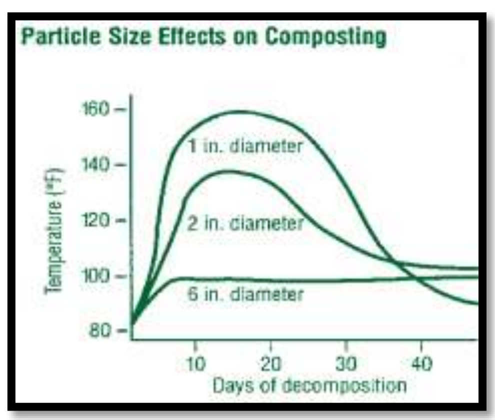


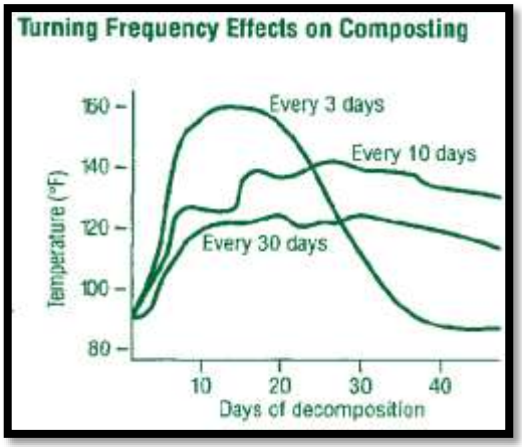
Figure 2: Phases of Composting

Compost Efficiency

The heating source is inside the compost heap as its chemical and biological reaction go on. The compost particle size, C/N ratio, turning, and pile volume have great effect on temperature yield, as shown in the graphs below:







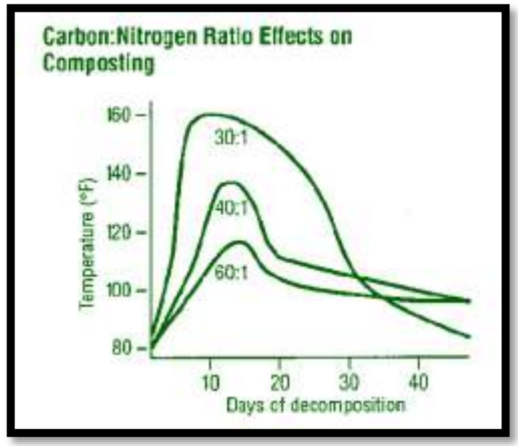


Figure 3: Composting Effect
(Pictures from *Urban Composting* at http://www.urban-composting.com/composting-tutorial.html)

Based on these relations, we now see the possible control on temperature yield from compost, and it depends on its pre-treatments and ongoing treatments such as pre-turning, material compaction, material substrate mixture, and continuous turning.

An in-vessel composting system has an advantage in temperature yield due to its homogeneous microbial activities inside the compost material. It also doesn't have large temperature gradients found in other composting methods such as windrow piles. Since the primary goal of the design is heat extraction, the composting system may be compromised. Trying to enhance temperature may not only inactivate pathogen but also eliminate "good" microorganisms. Experiments must be conducted and a pattern for the process must be found to prevent inactivation of nutrients and positive microbial activities.

Mechanisms of Heat Transfer

The temperature at any point during composting depends on how much heat is being produced by microorganisms, balanced by how much is being lost through conduction, convection, and radiation. Through conduction, energy is transferred from atom to atom by direct contact; at the edges of a compost pile, conduction causes heat loss to the surrounding air molecules.

Convection refers to transfer of heat by movement of a fluid such as air or water. When compost gets hot, warm air rises within the system, and the resulting convective currents cause a steady but slow movement of hot air upwards through the compost. In addition to this natural convection, some composting systems use "forced convection" driven by blowers or fans. This forced air, in some cases is triggered by thermostats that indicate when the piles are beginning to get too hot. Much of the energy transfer is in the form of latent heat -- the energy required to evaporate water. We can sometimes see steamy water vapor rising from hot compost piles or windrows.

The third mechanism for heat loss, radiation, refers to electromagnetic waves like those that you feel when standing in the sunlight or near a warm fire. Similarly, the warmth generated in a compost pile radiates out into the cooler surrounding air. The smaller the compost pile, the greater the surface area and the larger heat loss to conduction and radiation.

Previous Work

In the “DESIGN II” part of this project, our team wanted to determine the optimal way to provide heat to a greenhouse from compost. Several alternative designs where considered and we established that the “wheelie bin” style compost heat exchanger was the best way to extract heat from compost. This method was chosen over the others mainly because it had lower initial costs and maintenance costs as well as providing a more controllable composting process. Furthermore the “wheelie bin” style composter is very simple and does not harm the environment. In order to actually provide the extracted heat from the composter through the means of heated water to the greenhouse, we proposed a system of root zone water pipes with coaxial geometry. These copper pipes are not costly and can easily be adjusted to the needs of our design. The purpose of the coaxial geometry was to provide more uniform temperature distribution in the greenhouse and we decided to put these pipes in the root zones of the plants in order to keep temperature at a maximum around the plants themselves, opposed to near the extremities of the structure.

Our final design proposal was the “KAL-3” system and a rough outline of it can be seen in figure 4;

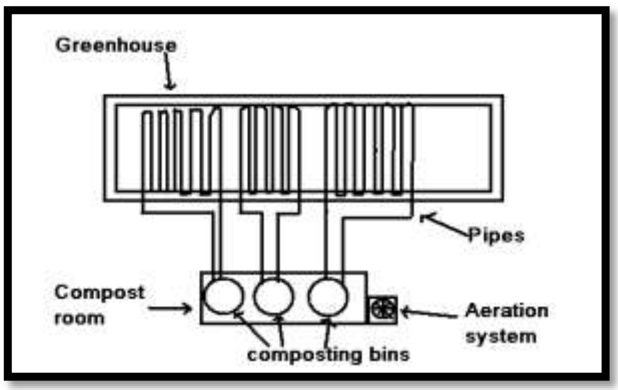


Figure 4: Design 2 Proposal

Objective and Goals

The objectives and goals of the overall design need to be achievable as well as work in unison. The objectives are; 1) to harness biothermal energy from a compost mass and 2) to reduce the energy demands of a standard heated greenhouse. For choosing a size of greenhouse, one of two smaller greenhouses located next to Mac Market at McGill`s Macdonald Campus was selected.

Figure 5 – Top View of Greenhouses

Measurements of Greenhouse

Width (w) = 220 in. = 5.588 m

Length (L) = 96 ft = 29.26 m

Height (h) = 111 in. = 2.8194 m

$$Floor\ Area\ =\ 163.5\ m^2$$

$$\boldsymbol{Volume\ of\ Greenhouse\ =\ w \cdot L \cdot h\ =\ 461\ m^3}$$

Several steps need to be taken to understand biothermal energy as a viable alternative energy technology. Parameters for modelling can vary widely therefore specific conditions will be set and the system will aim to be optimized for the best results. Before simulation can begin, there is a range of preliminary questions to be answered.

- How much of a specific type of compost is needed to heat a specific size of greenhouse?

- How much excess heat can be harnessed from a composting process to space heat an adjacent structure such as a greenhouse?
- How long can the compost maintain the desired temperature levels and will the compost process be optimized or will it have to be compromised to meet the heating requirements?
- How will the heat from the compost be transferred from one area to another?
- What will be the most favourable design for economic optimization? Can the system provide an reasonable payback period?

After all, we need to have a clean and simple system. It will aim to be appealing to a greenhouse operator or farmer and present little to no additional work. The compost process will aim to be controlled and have limited odour which can be achieved with in vessel composting (Viel et al,1986). Goal number two is a hydronic system. A hydronic system is one that uses water as the heat transfer medium. In the past experiments have been conducted using forced air systems to capture the heat (LoCasio, 2001), (Fulford, 2005). The compost heat or exhaust gases are captured and then expelled into the greenhouse. An intermediate step is usually required to filter or scrub the air. Jean Pain's original design was a hydronic system that produced hot water. Using water can be clean and simple and re-circulating pipes can be installed. Goal number three coincides with goal number one; the system must be user friendly and easy to operate. Once in place, the operator will need to know how long it the machine can operate and how effectively. The system will be fitted with sensors as well as a smart program to know when the compost heap has past its thermophilic stage. The last goal will be related to economics. This system put into place will need to offset costs of heating a significant amount and not be too expensive.

Keep in mind that any assumptions made contain an uncertainty and can therefore affect the system optimization, however they have been chosen to be as accurate as possible. Such a system is very dependent on its unpredictable components and therefore it is an important to acknowledge this statement.

Heat Losses

Greenhouse

Heat losses can occur at many locations in the system with the greenhouse being the largest since it occupies the most space. Heating needs for the greenhouse will be analyzed using the methodology presented by Nelson for a double poly coated Quonset (free standing) greenhouse (Nelson, 1998):

$$\boldsymbol{H} = (\boldsymbol{R} * \boldsymbol{K} * \boldsymbol{C_R}) + (\boldsymbol{S} + \boldsymbol{K} + \boldsymbol{C_S}) \qquad \textbf{[MBtu/hr]}$$

Where **H** equals the heat loss of the greenhouse, **R** and **S** are the standard heat losses for the roof and side walls respectively, **C** is the coefficient for glazing material and **K** is the adjustment temperature for wind and temperature. **K** is chosen from tables using average scenario temperature and wind speeds. For a floor area of 163.5 m^2, the heat losses were calculated at 0.279 MBtu/hr or 81.75 kW. This is equivalent to a loss of 500 W/m^2.

Compost

Heat losses due to ambient air temperature are a concern since composting will need to occur during the coldest months of the year. In-vessel composting will provide some insulation but the cold will still be a factor and therefore additional insulation will be required. Insulation of 0.05 m surrounding the pile can expect 40-80% heat loss can, 0.12 m insulation protects up to 20-40% heat loss, and to minimize heat loss to below 10% 0.45 m of insulation will be required (Gilson, 2009). Appropriate materials can include recycled foam or glass wool.

Intermediate

Hot water exiting the compost tank and entering the greenhouse is subject to heat losses to the surrounding air. Calculating the heat losses can be done using forced internal flow theory and comparing the temperature difference between outlet and inlet (Holman, 1981). A stainless steel pipe will be installed underground with an outer diameter of 0.11m and an inner diameter of 0.1m. The surrounding soil will be worst case scenario of -30 C. The depth and distance between source and sink can be modified but first the overall heat transfer coefficient needs to be determined.

$$Re_{DH} = (U_{AV} D_H)/\nu \qquad \textbf{[Dimensionless number]}$$

Since $U_{AV} = m/(\dot{\rho} A_{CS})$ and $D_H = 4A_{CS}/P$, the Reynolds number can become;

$$Re_{DH} = (4\dot{m})/\rho\nu P \qquad \textbf{[Dimensionless number]}$$

Where $\dot{m}$ is the mass flow rate, ρ is the density of water in kg/m^3, υ is the kinematic viscosity in m^2/s and **P** is the perimeter in metres. The system has a mass flow rate of 0.5 kg/s to allow for a turbulent flow since turbulence has better heat transfer capabilities (Holman, 1981). The Reynolds number is equal to 16,500 and it is therefore turbulent and can be modelled using an appropriate Nusselt correlation to determine its **h**.

$$Nu_{DH} = 0.023Re\hat{}(4/5)Pr\hat{}(0.4) = \ hD/k \qquad \textbf{[Dimensionless number]}$$

Pr is the dimensionless Prandtl number and **k** is the thermal conductivity of flow. Calculating **h** results in a value of 432.78 W/m^2 for the heat conduction inside the pipe. The overall heat transfer coefficient (**U**) is calculated as follows.

$$UA = 1/h_i A + ln(D_o/D_i)/2\pi L k_{ss} + 1/Sk_{ground}$$

Where **L** is the length of pipe and **S** is the soil shape factor equal to $2\pi L/\cosh^{-1}(2Z/D)$ where **Z** is the depth of the pipe and **D** is the diameter all in metres. The heat difference can then be calculated using the following equation.

$$\dot{m}c_p(T_o - T_i) = UA(T_o - T_i)/ln(T_{sfc} - T_o)/(T_{sfc} - T_i)$$

Where the subscripts **o**, **i**, and **sfc** represent the temperature of the fluid at the outlet, inlet and the surface of the pipe respectively. Therefore, to expect zero heat loss i.e. $(T_o - T_i)$ to equal 0.001, the ranges of values for distance and depth are; 0 m < L < 2.1 m and 0.5 m < depth <1.37 m (frost line).

Overall, the greenhouse dissipates a large quantity of heat and compensating this loss is very resource intensive. It will require considerable amounts of compost if it is the sole heat provider, therefore the goal will be slightly modified. The system will work in conjunction with a hot water tank located inside the greenhouse. The hot water tank can control the temperature and flow of water through the heat pipes in the greenhouse. The compost pile will aim to heat the water to a temperature of 45 °C and then store it in the hot water tank from where it can be distributed. The hot water tank can then raise the temperature of the water if needed.

Design Parameters

In order to facilitate the analysis of the design parameters of our theory we divided them into two main categories; the source and the sink. The source represents theory occurring in the compost reactor, where compost is the source of heat. The sink is the recipient of this heat, the greenhouse.

Source (Compost)

Since compost is highly variable by nature and temperatures can vary by composition it is important to have a solid reference point for designing the system. In vessel composting allows for a more controlled process. The closed system allows shortening of mesophillic and thermophillic phases while producing a higher efficiency and decreased number of pathogens (Viel et al, 1986). The closed system is also consistent with the main goals. Optimal temperature can vary depending on the source but it is important to note that temperatures do not exceed 60-65 °C because it can be harmful to the organisms present. Moisture levels will need to be high (50-60%) and watering may be necessary to allow continual decomposition. The optimal carbon to nitrogen balance (C:N) will be around 30:1 to allow for a stable environment for microorganisms as well as provide a good compost end product. Compost values used as a basis for calculation are taken from Viel's paper.

Physico-chemical Characteristics of the Constituents of the Composting Mixture (% on a Dry Matter Basis)

Constituents (%)	*pH*	*% dry matter*	*% ash*	*% N*	*% C*	*C/N*	*% P*
Anaerobically digested sewage sludges (32)	6·8–7·0	21–23	40–45	2–3·5	30–35	≃10	1·3
Flotation foams (8)	5·3–5·5	40–55	3–6	0·8–1·2	75–80	≃80	0·24
Poplar sawdust (60)	8·5–8·9	55–70	1·5–3	0·1–0·2	46–50	≃300	0·003

Table 1: Compost Properties

The desired temperature at outlet would be estimated around 45°C with a mass flow rate of 0.5 kg/s. Energy recovered can be calculated by direct measurement of the water flow rate, and the inlet and outlet temperatures (Holman, 1981). Given a steady inlet temperature of 5℃ the energy recovered would be:

$$q = \dot{m}c_p\Delta T \qquad \textbf{[W]}$$

Where **q** is the energy recovered, c_p is the specific heat capacity of water at 4204 J/Kg*k and ΔT is the change in outlet and inlet temperature. The formula yields a value of 84,080 W to raise water by 40 degrees.

Theory

Determining the energy value of compost can be difficult as no compost is created alike. The system will run a pipe through the compost pile and extract the heat. The total energy $\mathbf{E_T}$ (kcal per kilogram of dry matter starting material) can be split into 4 components. Each can all be calculated separately using the thermal balance of in-vessel composting.

$$E_T = E_C + E_D + E_G + E_R \qquad \textbf{[Kcal/Kg]}$$

Where E_C is the energy stored within the composting mass and the reactor, E_D is the energy dissipated through the walls of the reactor in spite of the thermal insulation, E_G is the energy removed through the effluent gas and E_R is the energy removed through the thermal exchanger. Electrical energy used for mixing and aeration is not considered in the thermal balance. The values for E_R can range significantly depending on heat recovery. Results reported were between 4 - 28 W/kg for 5 days given a total energy value of 30 W/kg. For modelling a value of 15 W/kg will be chosen. Given our initial energy calculation of 84,080 W and a compost density of 710 kg/m^3, the required mass of compost to produce that heat is 5,605.33 kg.

Designing the Heat Exchanger

A helical coil heat exchanger design provides the most optimal setup considering space limitations. An interior coil will give the most surface area and contact with the compost pile. Traditionally a heat exchanger exchanges heat between two fluids but this design will be modified to use compost. The heat exchanger will be modelled for compost temperature ranges between 40 and 60°C. The helical coil pipe heat exchanger would normally be used for many continuous system having rather smaller heating duties. This kind of exchanger is better in cases of limited space for piping and more economical with lower heat transfer coefficient.

Sizing the bin will be based on the mass of compost used for 5 days. Given 5,605.33 kg of compost with a density of 710 kg/m^3 will need to fit in the bin, the volume of the tank will need to be 7.90 m^3. This means a diameter of 1.83 m, a length of 3 m and a coil radius of 0.46 m.

In this part of our design, the heat transfer coefficient outside of coil h_0 is first to be determined. In order to calculate this coefficient h_0, we would need to make the following assumptions; radiation in the pipe can be neglected, properties remain constant, $u/u_w \rightarrow 1$, flow in the pipe is fully developed $L/D > 10$ and temperature of the surface is equal to temperature of the ambient air or compost. Copper of type L is used as the coil.

Properties of copper (Type L):

d_o = 1.125 in = 0.028575 m

d_i = 1.125 in – 0.050 in = 0.027305 m

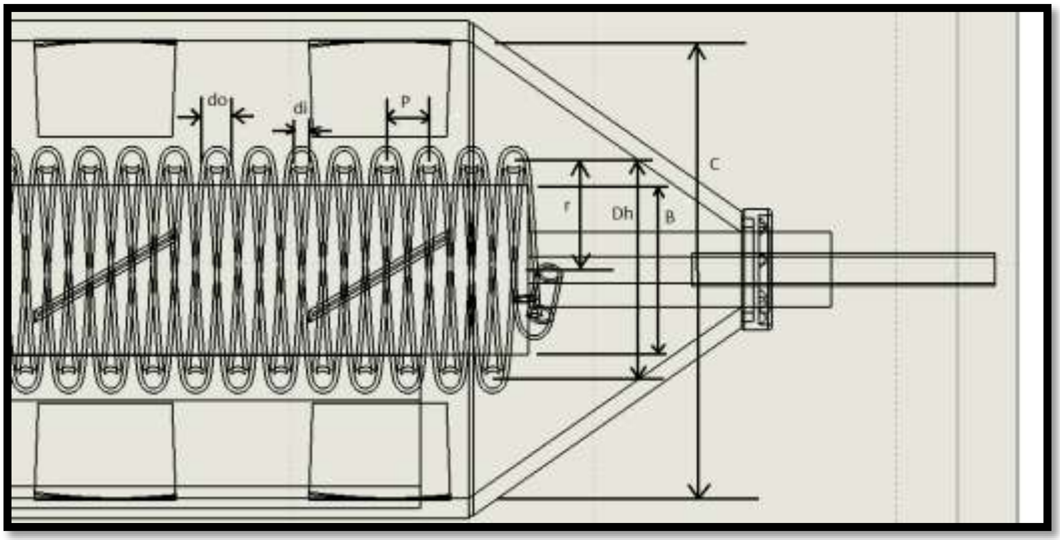


Figure 6: Side Cross-Sectional View of Coil Pipe

Length (***L***) and turns (***N***) of coil pipe: $L = N * sqrt[(2\pi r)^2 + p^2]$ where ***p*** is spacing between turns, and ***r*** is radius of coil;

- Volume of coil $V_c = (\pi/4)d_o^2L$ where d_o is outside diameter of coil;
- Volume of inner cylinder $V_i = (\pi/4)(C^2 - B^2)pN$ where ***C*** is diameter of compost bin, ***B*** is diameter of inner cylinder;
- Volume of coiled tube $V_f = V_i - Vc$;
- Diameter of coiled cylinder $D_e = 4V_f / \pi d_o L$.

Before find out the heat transfer coefficient h_o, we need to calculate Reynolds number ***Re*** by applying the following equation:

$h_oD_e/k = 0.6Re^{0.5}Pr^{0.31}$ where ***k*** is the thermal conductivity of fluid, and ***Pr*** is Prandtl number($c_p\ \mu / k$);

if **Re** is over 10000, the equation should turn to:

$h_oD_e/k = 0.36Re^{0.55}Pr^{1/3} (\mu / \mu_w)^{0.14}$ where μ is fuild viscosity at bulk-fluid temperature, μ_w is fluid viscosity at pipe wall temperature.

The heat transfer coefficient inside the coil h_{oi} can be found by the ratio of inside diameter of coil to outside diameter: $h_{oi} = h_o(d_i/d_o)$

Then the overall heat transfer coefficient U is given by:

$1/U = 1/h_o + 1/h_{oi} + (d_o-d_i)/2k_c + R_a$ where k_c is thermal conductivity of coil wall, R_a is fouling factor of compost bin. The fouling factor will be neglected.

Final Dimensions

The HCHE is optimized to have the following dimensions:

- Length of copper pipe = 23 metres
- Number of turns = 23

Sink (Greenhouse)

The greenhouse is where the gathered energy will be used to increase the overall temperature inside the greenhouse by means of circulating warm water in pipes. In fact, the heated water coming out of the compost bin heat exchanger, as explained in the previous section, will be first stored in the water tank and then released in the pipes inside the greenhouse. The Temperature Control System will regulate the mass flow rate from the water tank to pipes inside the greenhouse. These pipes inside the greenhouse will be made out of copper since we previously established that copper has a high conductivity.

Theory and Calculations

The process of heating a greenhouse or any space with hot or warm water is in general terms very simple; water at a higher than ambient temperature flows in long pipe at a certain mass flow rate, and through conduction and convection some of its energy is transferred to the ambient air, increasing its temperature. The overall total energy transferred to the greenhouse is calculated in terms of Joules **[1 J (Joule) = 1 W (Watt) x 1 s (second)]**.

The basic theory comes from the 1st Law of Thermodynamics;

$$\Delta \boldsymbol{E} = \boldsymbol{W_{in}} + \boldsymbol{Q_{in}} \qquad \textit{[J]}$$

Where the input of energy in the form of work ($\boldsymbol{W_{in}}$) plus the input of energy in the form of heat ($\mathbf{Q_{in}}$) must equal the increase in energy stored ($\Delta \boldsymbol{E}$) in a control volume. In our situation, there is negligible energy in the form of work ($\boldsymbol{W_{in}} = \mathbf{0}$) and the control volume is the volume of the greenhouse. Our goal, and therefore our first assumption is that we want to increase the temperature inside the greenhouse by 3 °C. Therefore using Newton's Law of Cooling we can equate the energy stored in the control volume ($\Delta \boldsymbol{E}$) to the energy needed to raise the temperature inside the greenhouse by 3 °C with the following formula;

$$\Delta \boldsymbol{E} = \boldsymbol{Q_{GH}} = \boldsymbol{m c_p \Delta T} = (\boldsymbol{V\rho})\boldsymbol{c_p}(\mathbf{3}\boldsymbol{K}) \qquad \textit{[J]}$$

Given that the total volume (**V**) of air in the greenhouse is 460 m^3, and that air has a density ($\boldsymbol{\rho}$) of 1.205 Kg/ m^3 and a specific heat of 1005 J/Kg*K at a temperature of 20 °C, the previous equation will result in the following;

$$\Delta \boldsymbol{E} = \boldsymbol{Q_{GH}} = \left(\mathbf{450\ m^3} * \mathbf{1.205}\frac{\boldsymbol{Kg}}{\boldsymbol{m^3}}\right) * \mathbf{1005}\frac{\boldsymbol{J}}{\boldsymbol{Kg * K}} * \mathbf{3}\boldsymbol{K} = \mathbf{1.6\ MJ}$$

A total of **1.6 MJ** is needed to increase the temperature inside the greenhouse by 3 °C. Going back the 1st Law of Thermodynamics, we can derive the following;

$$Q_{GH} = \Delta E = W_{in} + Q_{in} = Q_{in}$$

$$Q_{in} = Q_{GH} = 1.6\ \text{MJ}$$

The input of energy in the form of heat (Q_{in}) is equal to the rate of energy lost by the flow of water ($\dot{q}$) multiplied by the amount of time (t) during the which water circulates;

$$Q_{in} = \dot{q} * t \qquad [\text{J}]$$

The rate of heat transfer or rate of energy transfer is obtained from the following equation;

$$\dot{q} = \dot{m}c_p(T_{bi} - T_{bo}) \qquad [W]$$

$\dot{m}$ [Kg/s] is the mass flow rate of water, c_p is the specific heat of water (4181 J/Kg*K) and T_{bi} and T_{bo} are the inlet and outlet temperature of water in Kelvin [K]. The goal of the compost heat exchanger discussed in the previous section was to provide water at a temperature of 45°C and at a mass flow rate of 0.5 Kg/s. The only unknown is therefore the outlet temperature, T_{bo}.

Our design situation is physically explained as an internal forced fluid flow in circular pipe exposed to constant outside fluid cross flow and the temperature at the outlet (T_{bo}) can be obtained from the following equation;

$$T_{bo} = T_\infty - \left((T_\infty - T_{bi}) * \exp\left[-\frac{P_i L}{\dot{m}c_p}\overline{U_o}\right]\right) \qquad [K]$$

$\boldsymbol{T_\infty}$ is the ambient temperature and it's assumed to be 23°C (296 K). $\boldsymbol{T_{bi}}$, $\boldsymbol{\dot{m}}$ and $\boldsymbol{c_p}$ are known and are respectively 45°C (318 K), 0.5 Kg/s and 4181 J/Kg*K. The only unknown is therefore the overall the overall average heat transfer coefficient $\overline{\boldsymbol{U_o}}$ expressed in $[\frac{W}{m^2*K}]$.

$\overline{\boldsymbol{U_o}}$ This overall average heat transfer coefficient depends on the sum of the individual resistances for which a thermal circuit in shown in the following figure;

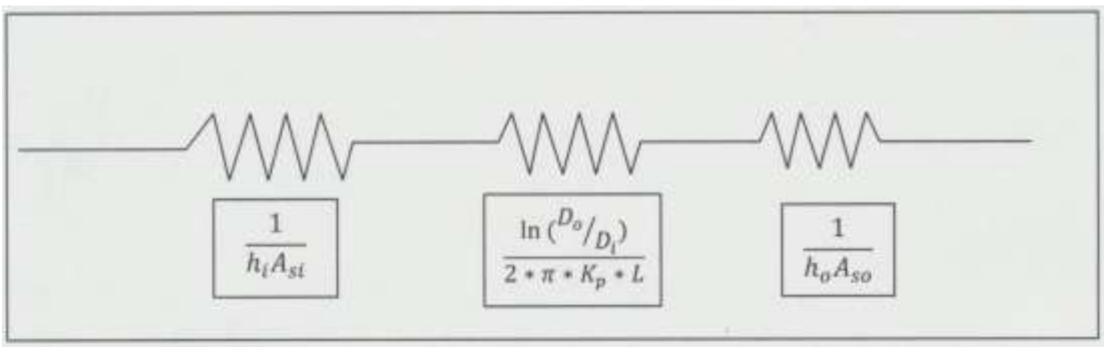


Figure 7: Thermal Resistance Circuit

This overall heat transfer coefficient $\overline{\boldsymbol{U_o}}$ is calculated with by the following formula;

$$\overline{U_o} = \left(\frac{A_{so}}{h_i} + \frac{A_{so} \ln\left({D_o}/{D_i} \right)}{2\pi K_s L} + \frac{1}{h_o} \right)^{-1} \qquad [{W}/{m^2K}]$$

Where $\boldsymbol{A_{si}}$ and $\boldsymbol{A_{so}}$ are the inner and outer surface areas of the pipe is [m^2], $\boldsymbol{D_i}$ and $\boldsymbol{D_o}$ are the inner and outer diameters of the pipe [m] and **L** and $\boldsymbol{K_s}$ are respectively the total length of the pipe [m] and the thermal conductivity coefficient of the pipe $[\frac{W}{m*K}]$. The two unknown values are $\boldsymbol{h_i}$ and $\boldsymbol{h_o}$.

$\boldsymbol{h_i}$ is the convective heat transfer coefficient of water and obtained from the following equation;

$$h_i = \left(\frac{K_f}{D_H}\right) * Nu_i \qquad \left[{}^{W}/{}_{m^2K}\right]$$

Where $\boldsymbol{K_f}$ is the thermal conductivity of water $[\frac{W}{m*K}]$, $\boldsymbol{D_H}$ for a circular pipe is always equal to the diameter, thus in our case $\boldsymbol{D_H = D_i}$ [m] and $\boldsymbol{Nu_i}$ is the Nusselt Number of the flow obtained from the following equation;

$$Nu_i = 0.023(Re_D)^{0.8}(Pr)^{0.4} \qquad [-]$$

The Reynolds Number $(\boldsymbol{Re_D})$ is a characteristic of the flow and the Prandt Number ($\boldsymbol{Pr}$) is a property of the fluid. Both these dimensionless numbers can be calculated with the following equations;

$$Re_D = \frac{\bar{V}\,D_i}{v} \qquad [-]$$

$$\bar{V} = \frac{\dot{m}}{\rho A_{cs}} \qquad [{}^{m}/{}_{s}]$$

$$Pr = \frac{v}{\alpha} \qquad [-]$$

$\boldsymbol{\alpha}$ and $\boldsymbol{v}$ are respectively the thermal diffusivity and the kinematic viscosity of water, both in [m^2/s], $\boldsymbol{\dot{m}}$ is the mass flow rate of water [Kg/s], $\boldsymbol{\rho}$ is the density of water [Kg/m^3], $\boldsymbol{A_{cs}}$ is the inner cross-sectional are of the pipe [m^2] and $\boldsymbol{D_i}$ is the inner diameter of this same pipe [m].

$\boldsymbol{h_o}$ is the convective heat transfer coefficient of the air is obtained with the same formula used for the $\boldsymbol{h_i}$, that is;

$$\boldsymbol{h_o = \left(\frac{K_A}{D_H}\right) * Nu_o} \qquad \left[{}^{\boldsymbol{W}}/_{\boldsymbol{m^2K}}\right]$$

$\boldsymbol{K_A}$ is the thermal conductivity of air $[\frac{W}{m*K}]$ and $\boldsymbol{D_H}$ in this case is the outer diameter of the pipe $\boldsymbol{D_o}$ [m]. Again the only unknown is the Nusselt Number $\boldsymbol{Nu_o}$. For the case of outer cross flow on a circular cylinder, the Zhukauskas correlation must be used to find the Nusselt number $\boldsymbol{Nu_o}$;

$$\boldsymbol{Nu_o = C * {Re_L}^m * {Pr_\infty}^n * ({}^{Pr_\infty}/_{Pr_w})^{0.25}} \qquad [-]$$

$$\boldsymbol{Re_L = \frac{\rho * V * D_o}{\mu}} \qquad [-]$$

$$\boldsymbol{V = \frac{\dot{m}}{\rho A_{cs}}} \qquad [{}^{\boldsymbol{m}}/_{\boldsymbol{s}}]$$

$$\boldsymbol{Pr_\infty = \frac{v}{\alpha}} \qquad (\boldsymbol{evaluated\ at\ ambiant\ temperature}) \qquad [-]$$

$$\boldsymbol{Pr_w = \frac{v}{\alpha}} \qquad (\boldsymbol{evaluated\ at\ temperature\ of\ pipe\ wall}) \qquad [-]$$

$\boldsymbol{\alpha}$ and ***v*** are respectively the thermal diffusivity and the kinematic viscosity of air, both in [m^2/s]. $\boldsymbol{\dot{m}}$ is the mass flow rate of air [Kg/s] which depends on the number of air exchanges per hour, $\boldsymbol{\rho}$ is the density of air [Kg/m^3], $\boldsymbol{A_{cs}}$ is the outer cross-sectional are of the pipe [m^2] and $\boldsymbol{D_o}$ is the outer diameter of the pipe [m] and $\boldsymbol{\mu}$ is the dynamic viscosity of air [Pa*s]. **C,** ***n*** and ***m*** are factors that will depend on the Prandlt and Reynolds number in the following manner;

If	**Pr $\leq$ 10**	***n* = 0.37**
If	**Pr $\geq$ 10**	***n* = 0.36**

Reynolds	C	*m*
1 – 40	0.75	0.4
40 - 10^3	0.51	0.5
10^3 – 2*10^5	0.26	0.6
2*10^5 – 10^6	0.076	0.7

Table 2: C and *m* Parameters

Results

With all these formulas we will obtain $\dot{q}$ (the rate of energy transfer [W] and knowing the total amount of energy needed to increase the temperature in the greenhouse by 3 degrees (**ΔE = 1.6 MJ**), we can obtain the time needed (**t**) from the following formula;

$$t = \frac{\Delta E}{\dot{q}} \qquad [s]$$

We want to optimize the rate of heat transfer $\dot{q}$ because we want to increase the total efficiency of our design. In order to do so, it is important to understand that there are only certain parameters that can be "tweaked", the other parameters are set by the properties of the material itself. The parameters that we can adjust in order to make our design more efficient are the pipe material, the pipe thickness, the pipe width, the pipe length and the mass flow rate of water. In order to see the individual effect of each one of these 5 parameters, we created an excel sheet with the proper formulas embedded. From this excel sheet, we changed each design parameter individually and observed its effect on the total $\dot{q}$ [W] produced. The following tables show the effect of each adjustable parameter on the total $\dot{q}$ [W].

K of Pipe [W/m*K]	Total q[W]
0.1	1472.62
1	1788.1
5	1822.81
10	1827.24
25	1829.91
50	1830.81
100	1831.25
200	1831.47
400	1831.59
600	1831.78

Mass Flow Rate [Kg/s]	Total q [W]
0.1	1672.05
0.2	1768.36
0.3	1802.86
0.4	1820.68
0.5	1831.59
0.6	1838.96
0.7	1844.29
0.8	1848.31
0.9	1851.47
1	1854.01

Di	Total q [W]
0.01	730
0.02	1111
0.03	1476
0.04	1831
0.05	2178
0.06	2517
0.07	2850
0.08	3174
0.09	3492
Thickness 5mm	

Length of Pipe [m]	Total q [W]
10	291
20	580
30	868
40	1153
50	1437
60	1719
70	2000
80	2278
90	2555
100	2830

Table 3: Effect of Adjustable Parameters

We can clearly see that the two parameters that show the strongest effect on the total amount of energy transferred are the diameter and the length of the pipe. This means that optimal heat transfer depends on the total volume of water inside the pipes in the greenhouse. In theory, the longest and thickest pipe will offer the best results. In practice it is however unfeasible to do so and we must keep it to a reasonable size and length. We first estimate that a pipe with nominal diameter of 7 cm and a thickness of 5 mm would be sufficient for the purpose of our design. The second parameter, the length, is very crucial and will strongly influence the final results of heat transfer. We want the pipe in the greenhouse to be as long as possible but without any complicated geometries in order to keep our design the simplest. We estimate that feasibly a maximum length of 80 meters adequate. We estimate that this value is at a maximum because any further length will require too much volume. This volume inside the greenhouse is needed for equipment, plants and manoeuvrability.

We now have all the parameters needed to calculate the rate of heat transfer to the greenhouse in Watts. From our equations embedded in the excel sheet, we calculate that overall rate of heat transfer from our design is $\dot{\boldsymbol{q}} = \mathbf{2276}\,\boldsymbol{W} = \mathbf{2276}\ {}^{\boldsymbol{J}}\!/_{\boldsymbol{s}}$. Going back to our initial formula, in order to supply 1.6 MJ of energy to the greenhouse in order to raise its temperature by 3 degrees at a rate of 2276 J/s, we must run our system for 702 seconds, or about 12 minutes. This rate of heat transfer provided to the greenhouse, $\dot{\boldsymbol{q}} = \mathbf{2276}\ \boldsymbol{W}$ is very important and will be used later in the report to calculate the potential economical savings from our system.

Final Dimensions

The system of heat pipes inside the greenhouse will have the following dimensions:

- Length of copper pipe = 80 metres
- Inside Diameter = 7 cm

Overview of Parts

In this section of the report we will show and describe the main parts of our design. These parts were drawn with the computer software *SolidWorks*.

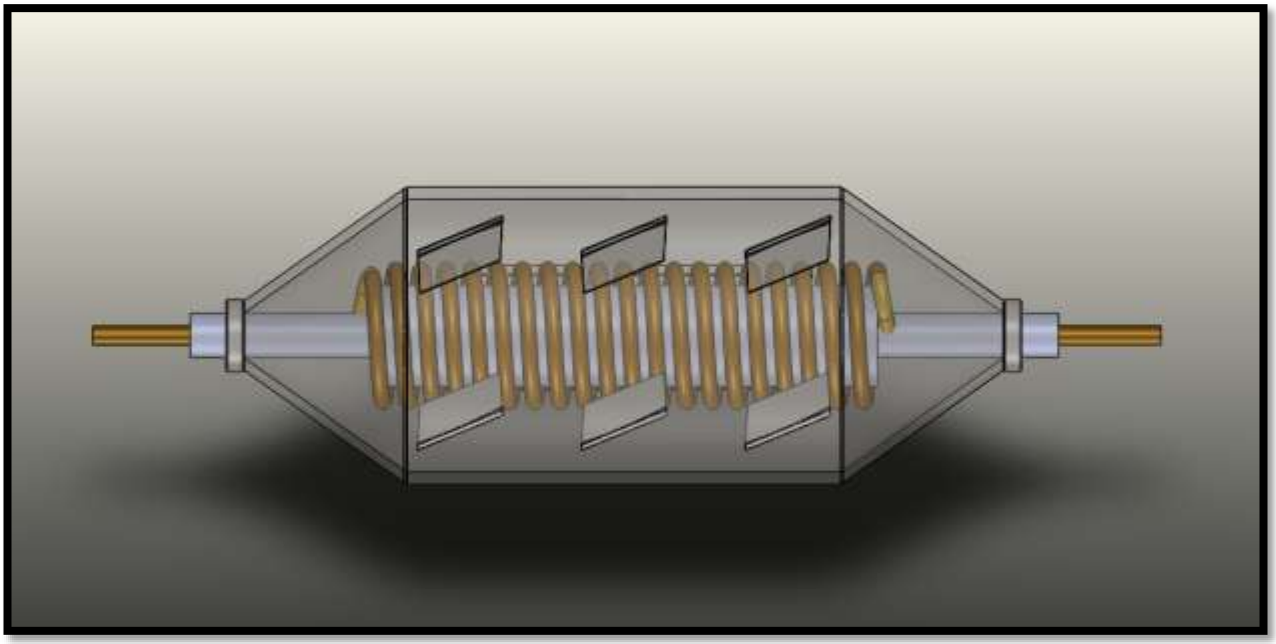


Figure 8: Cylindrical Composting Reactor

This is the front view of the design of the cylindrical composting reactor. The outer wall is set in transparent view. As illustrated above, there is a shaft throughout the cylindrical bin and a helical coil pipe wrapped around it. Water inlet and outlet are at the two extremities of the reactor.

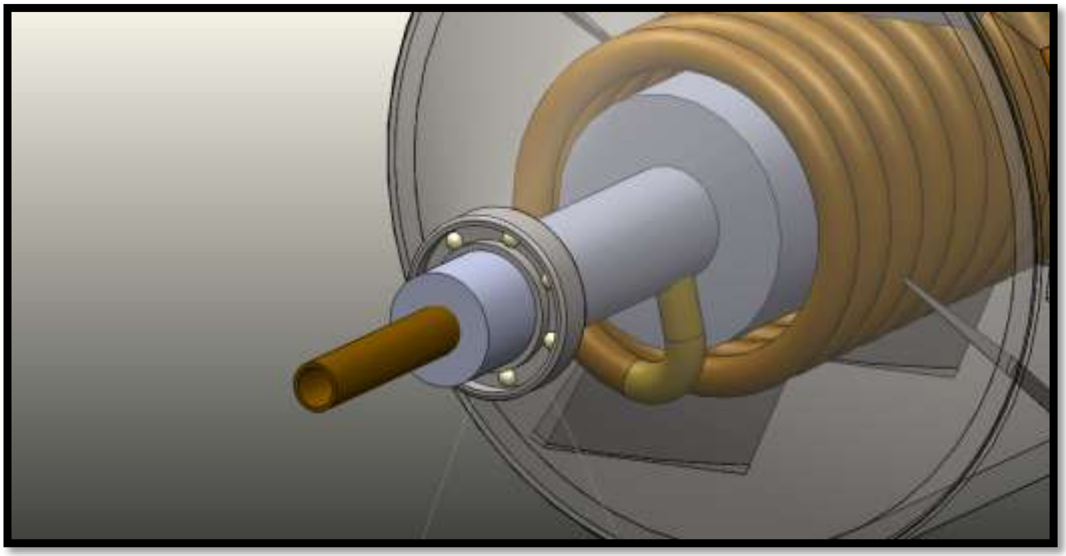


Figure 9: Coiled Pipes

The helical coil pipe outlet is illustrated in Figure 9 as well as the ball bearing (located on both ends) to allow the outer shell to rotate about the shaft while the helical coil pipe remains fixed.

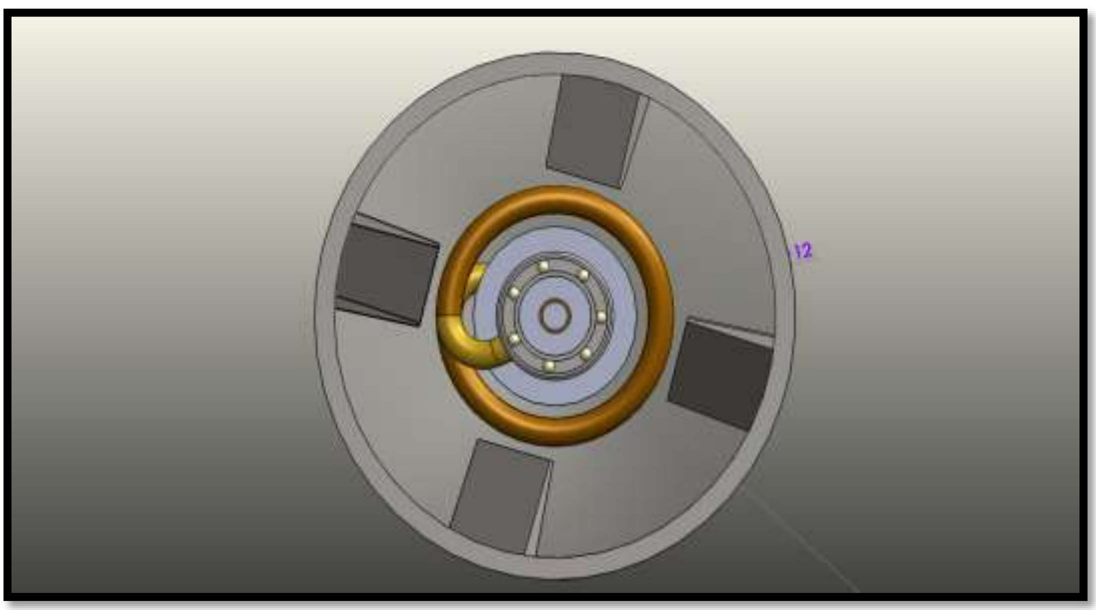


Figure 10: Top Cross-Sectional View of Reactor

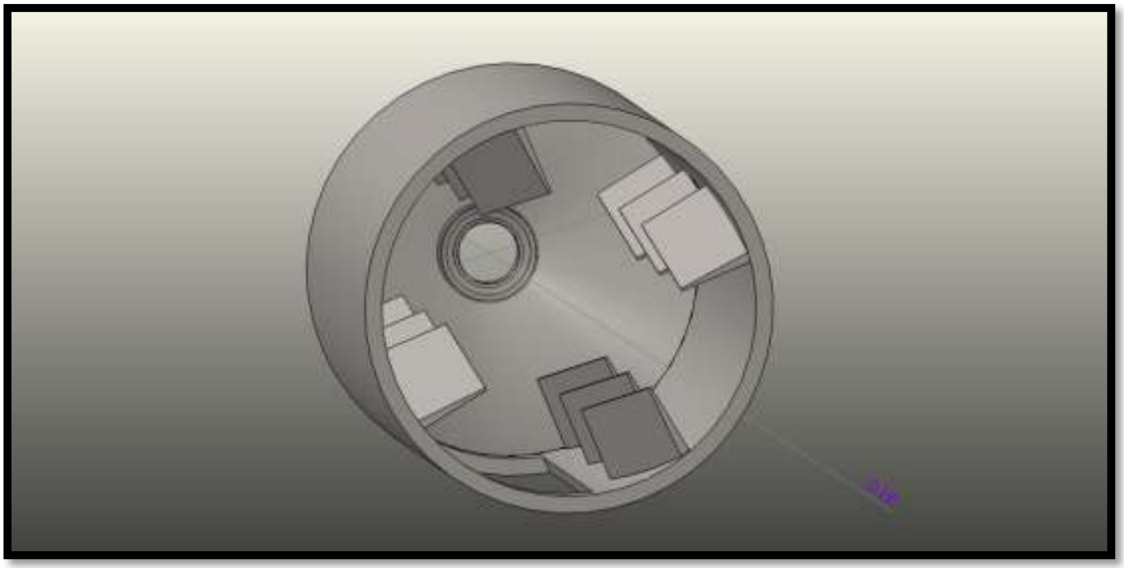


Figure 11: Reactor Blades

As clarified earlier, compost turning is one of the major factors in enhancing the biological reaction occurring inside of the compost material. Thus, we welded twelve turning blades on the inner wall of the composting reactor to facilitate the mixing process which will sustain the higher temperatures. The figure above illustrates the labelled dimensions of the coil pipe.

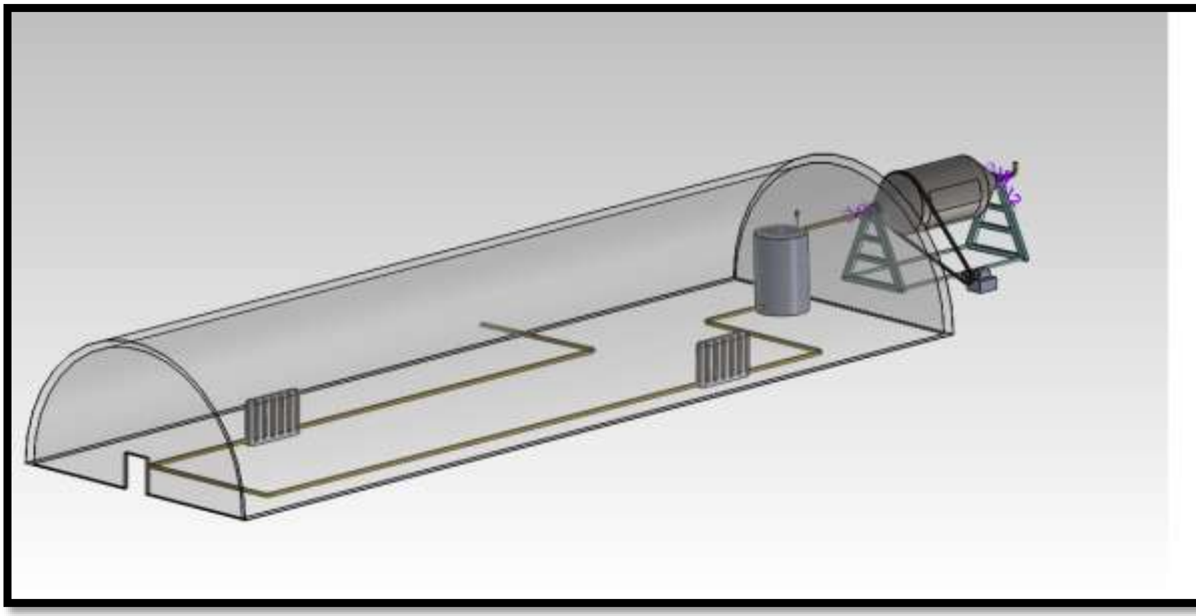


Figure 12: General View

The idea of the KAL3 system as a whole (Figure 12) is for re-circulated water to pass through the each component. Water from a reservoir enters the inlet of the composting reactor, where it is heated up by the natural compost heat. Water then flows out and accumulates in a hot water tank in the greenhouse (2) where its flow rate and temperature can be controlled for flow through the heat pipes. Radiators located along the walls enhance heat transfer and finally the flow returns to the reservoir to start over again.

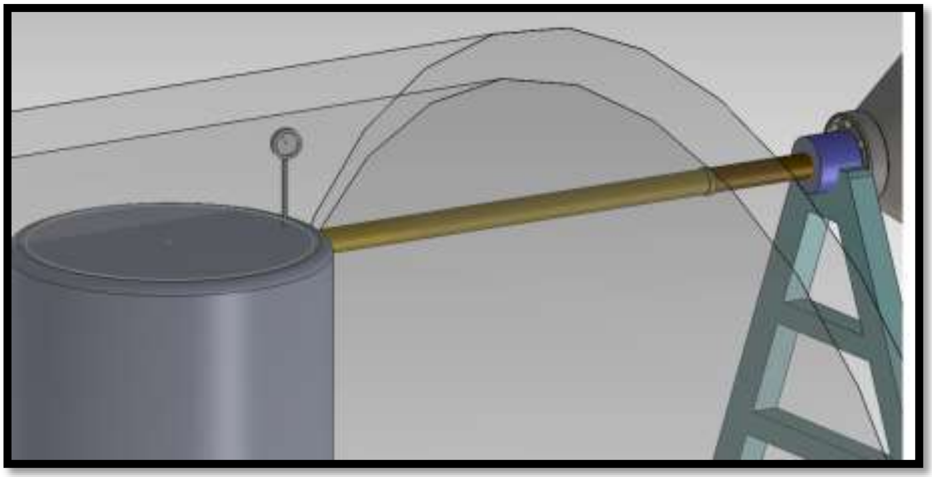


Figure 13: Water Tank with Gauge Monitoring Pressure

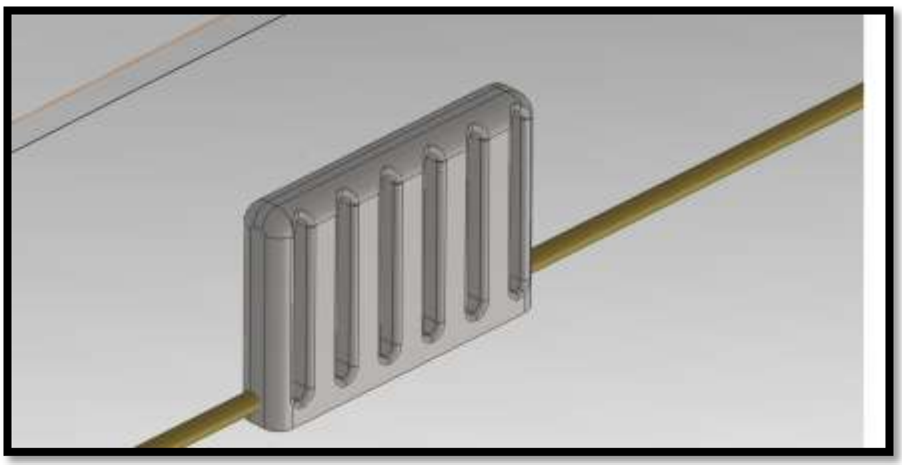


Figure 14: Radiator (increases overall heat transfer)

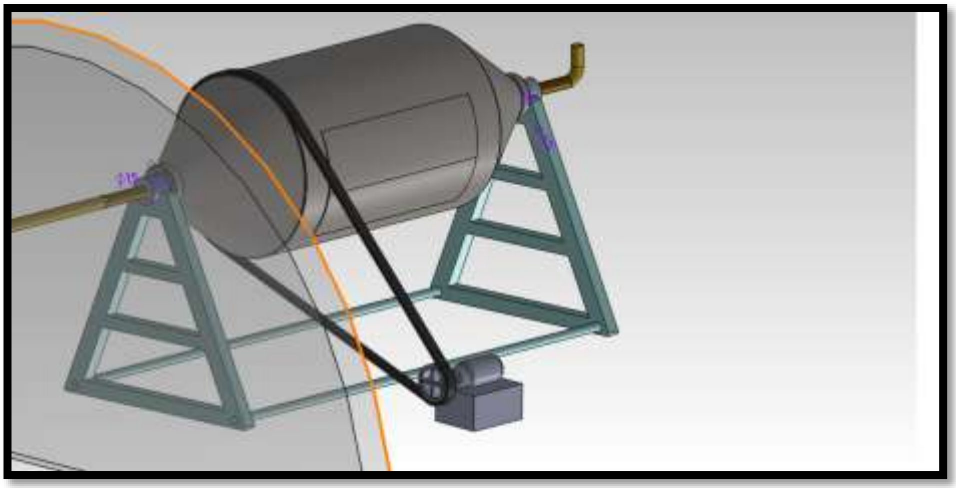


Figure 15: Electric Motor for Turning

An electric motor is connected to the composting reactor via a transmission belt (Figure 15) This will facilitate its rotation, since we expected a very heavy load of compost and man power may not be sufficient.

Temperature Monitoring System

Since the composting process cannot be precisely controlled by physical means and sometimes its temperature yield may exceed our expectations and potentially overheat the pile or the greenhouse a method was designed for monitoring and control of the temperature profile.

The temperature monitoring device uses a thermometer or RTD thermal sensor (with selected range from 0^oC to 90^oC) both inside the greenhouse and at the outlet of the composting bin. The control system is a *LabView* program and controlling the water flow through the greenhouse will allow for temperature control.

The diagram block of the temperature control system is shown below;

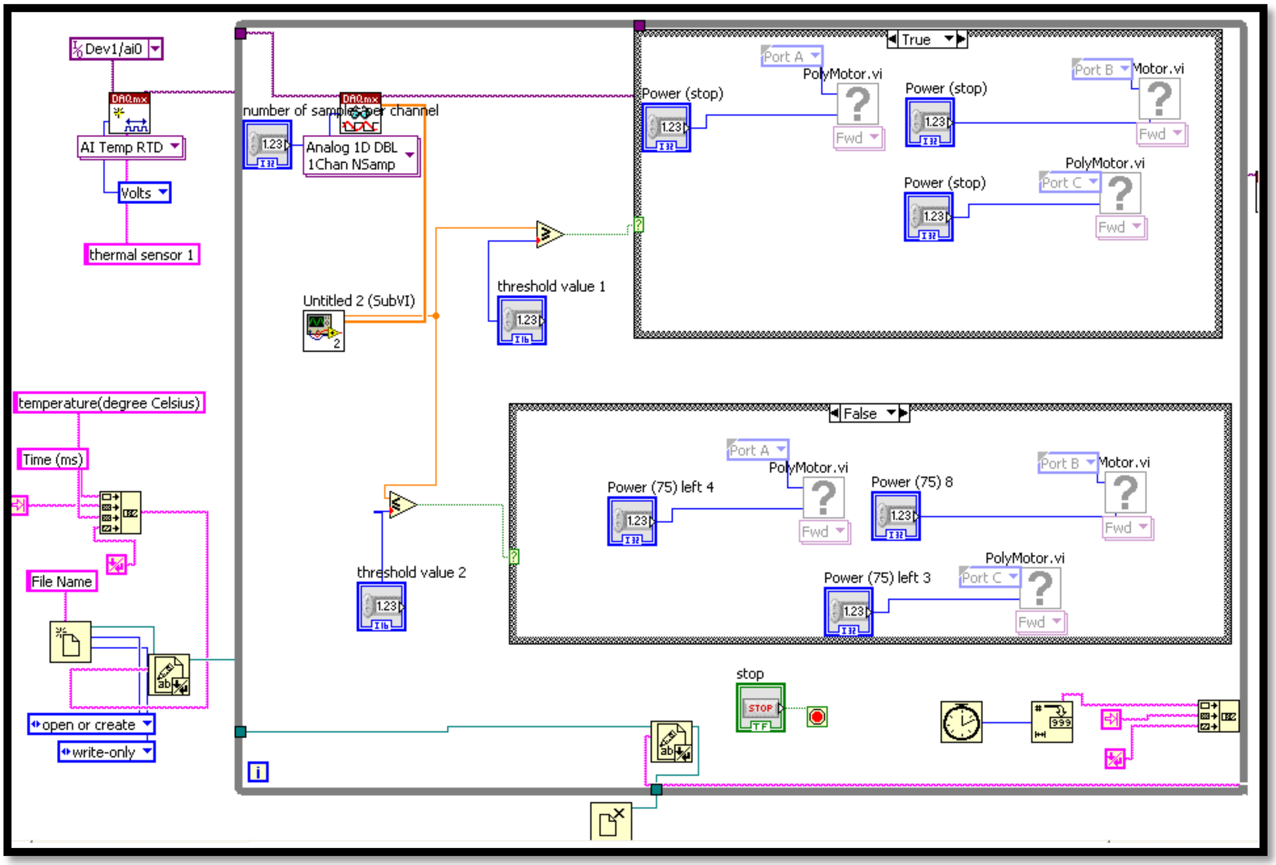


Figure 16: LabView Diagram Block

In this diagram, the data acquisition card (RTD sensor) reads temperature inside the heated space, and readings are transferred as analog input in volts into the while loop, then a calibration module subVI is created to convert the analog input to digital output in degrees Celsius. Afterwards, two threshold values are set for two case structures, and when temperature readings exceeds the expected threshold value 1 (true case), the adjustable functions inside this case will transmit a "power off" or "slow down" signal to a relay board(6) which control the water pump(7) to do so; or, when the temperature readings decreases and get lower than the threshold value 2, the functions in this case will send a "power on" or "speed up" signal to the pump. The same diagram can be used for the composting bin to monitor the temperature.

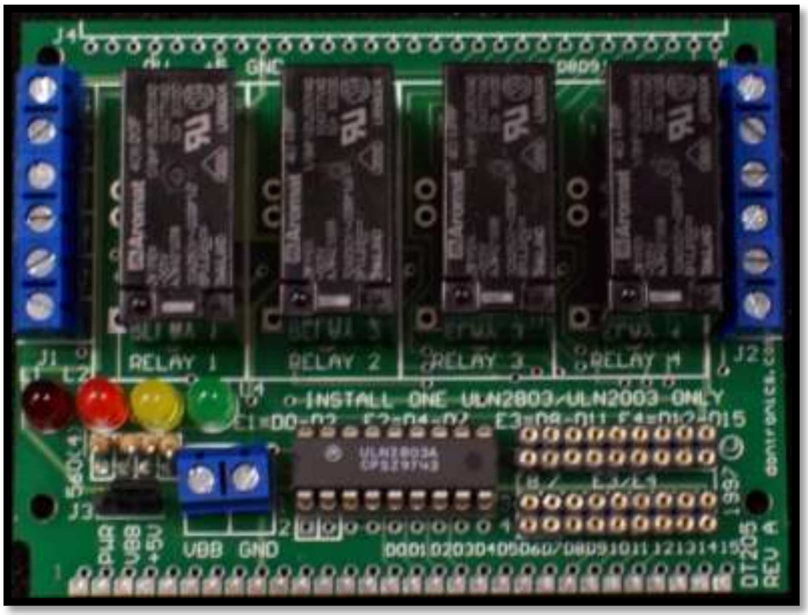


Figure 17: Relay Board

Once this system is implemented, the system can operate on its own, the temperature data against real time will be sent to owner's computer for further analysis or study and no extra worker is needed on site to monitor temperature change. Therefore the greenhouse should have a controlled temperature profile as shown below (Figure 18).

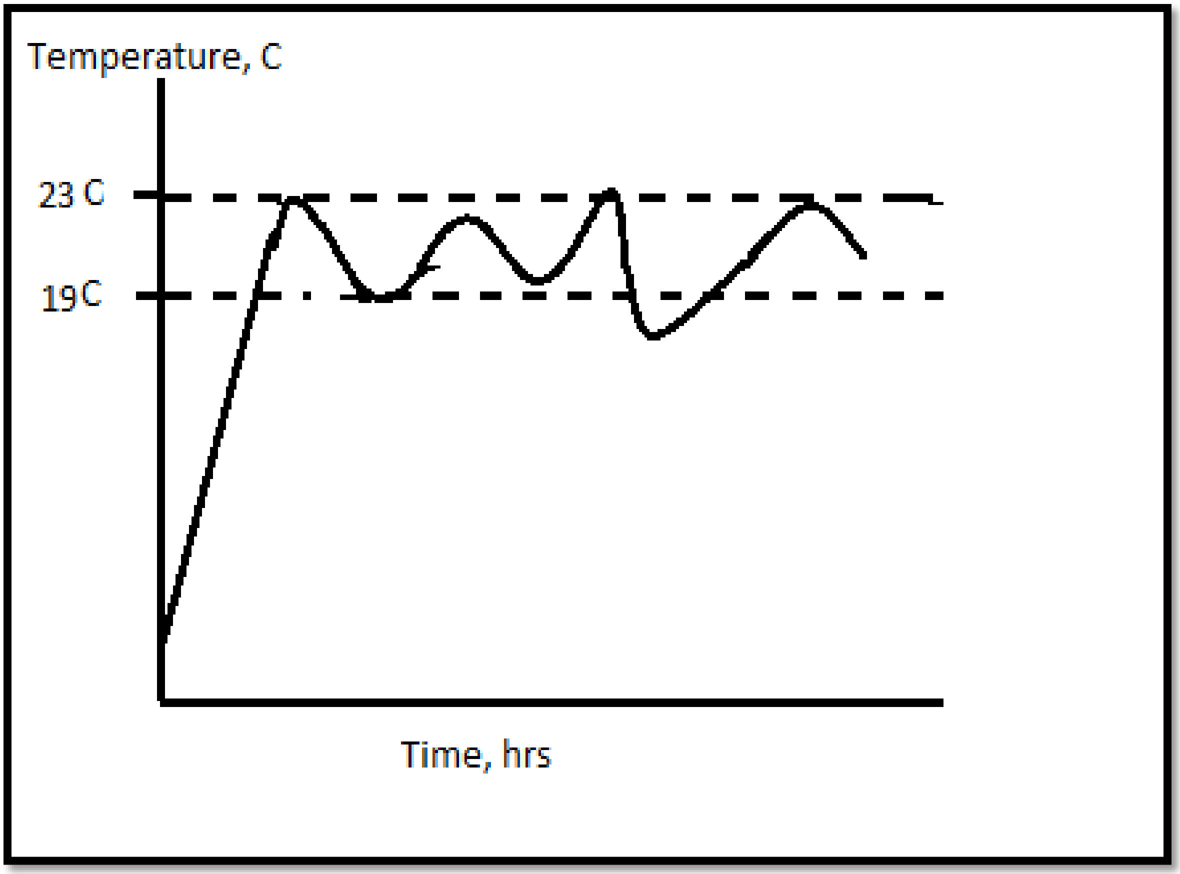


Figure 18: Temperature Variance

We primarily set the two threshold values at 19 and 23 °C, so the temperature shall remain in between them and the greenhouse can avoid being overheated or cooled down.

Re-Circulating System

The pipes exiting the greenhouse will have water at a temperature of roughly 44 degrees Celsius. Not using the heat potential of this fluid flow rate would be a waste. We thus propose to reintegrate this water in our system. It will re-integrate the system before the water enters the compost bin heat exchanger. This will strongly optimize the process of heat extraction from the compost since in our calculations it is assumed that the initial water flow rate entering the compost heat exchanger is at 5 degrees Celsius. Therefore, the re-circulating flow will mix with the initial, colder flow, and the mixture will be at an overall temperature greater than the 5 degrees Celsius we initially assumed. This will have for effect to diminish the heat extracted from the composting reaction and therefore diminish the impact on the temperature distribution of compost. In addition, with warmer water at the inlet we ensure that outlet water is kept at a temperature of 45 degrees Celsius or more for the duration of the 5 day thermophilic stage of the compost reaction. Thus, when we made the calculations necessary for our design, worst case scenario is always assumed. With this re-circulating system implementation, we ensure that the obtained results will never be lower than what we calculated. In fact, we estimate that if our design were physically built, it would offer better efficiency than in theory. The system will have better efficiency because the warm water heating the greenhouse will be at a higher temperature than we used for our calculation, thus providing more energy to the greenhouse. Ultimately, with a better efficiency, our system could require smaller amounts of compost while providing the same results or produce better results with same amount of compost. This will either have for effect to diminish the size, and therefore the cost of the compost tank or to increase the amount of energy produced, making our design more economically beneficial.

The re-circulating system implementation can be seen in the following figure;

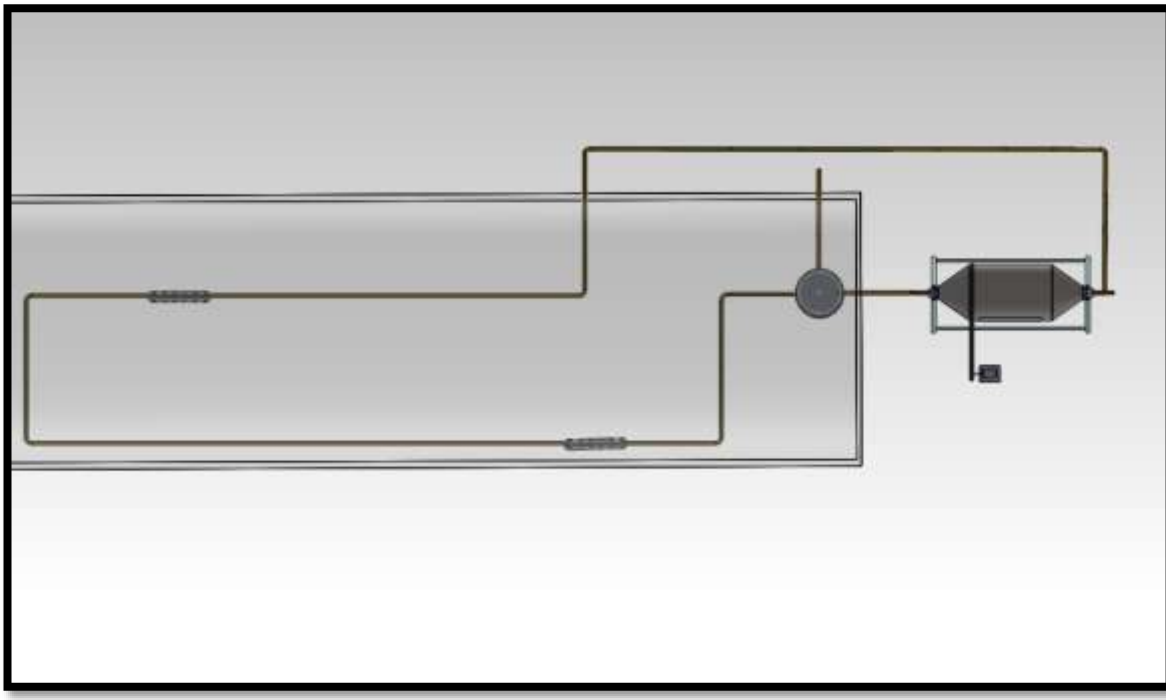


Figure 19: Re-Circulating System

Risk Analysis

The system needs to be assessed for different risks that can be associated with it. The constructed compost vessel can present many different failure modes. The vessel will weigh a lot, therefore it is optimal to have it on the ground to reduce possible mounting problems or risks associated if it falls. The design will always use a safety factor. Health considerations can also be an issue. It needs to be certain that the system does not sacrifice the compost process. There can be no harmful pathogens present in the end product since it may be spread on a field. The system can also pose a threat of overheating and becoming too hot. If the compost moisture levels are too low it can be prone to spontaneous combustion and therefore watering of the heap will be necessary.

Financial Analysis

Our design highlights compost as an alternative heating system for a greenhouse. Furthermore, the only input needed to achieve this goal is a manure composting mixture that we assume is readily available to the user. However, in order to see if our design is actually feasible, we must estimate all financial considerations needed for the implementation of such a system and the financial benefits the system would produce. In other words, we have to see if our design is financially possible and if so, what is the payback period?

There are two types of costs associated with our design, the initial cost and the operational cost. The initial cost is the amount of money needed to build and install the system and the operational cost is the annual amounts of money needed to operate it.

Initial Costs

Custom Compost Bin

The compost bin is the most expensive part of our design. In fact, we estimated that this compost bin needs to be able to hold up to 5 tonnes of compost. Our compost bin will be made out of 3 inch thick (0.0762 m) composite steel and have a total surface area of 14.26 m^2. This means that about 1.08 m^3 of composite steel and with a density of [7.5 tons / m^3] (Wisconsin, 1998) will have a mass of 8 tons. The selling price of composite steel is currently 770 $US per ton of raw material (WorldSteelPrices, 2012). Thus the cost of the raw material is 6000 $US. We estimate that the cost to produce this metal compost bin with our custom specifications (i.e. with blades for turning and holes for the entering and exiting water pipes) would be no more than 1000 $US. The platform with the ball-bearing needed to hold the compost tank in place and the base needed to support the weight will bring an additional cost of 700 $US, with installation. Finally the electric motor needed for the turning of the compost wouldn't cost more than 100 $US, assuming that the user doesn't already own one. Which brings the total cost of the custom compost bin to **7800 $US**.

Copper Pipes

The copper pipes are a very crucial aspect of our design as they are present both inside the compost tank and in the greenhouse. In total, we calculated that about 100 meters of copper pipes will be needed, with one fourth for the compost tank and the rest for heating the greenhouse. These copper pipes are readily available and they cost on average 13 $US per meter. The total cost for the copper pipes is therefore **1300 $US**.

Water Tank

The water tank is where the warm water from the compost tank will be stored at first and then, with the temperature monitoring system, sent through the system heat pipes in the greenhouse. We estimate that the maximum needed volume for such a tank is 2000 liter to allow for better efficiency of the system. Such water tanks are available and can cost **800 $US**.

Insulation

We want our system to be well insulated in order to minimize any possible heat losses. The compost tank, the water tank and parts of the copper pipe exposed to outside conditions need to be insulated. There are many types of insulations in the market and the cost is relatively low. We estimate that our design will not require more than **100 $US** worth to ensure proper insulation.

Radiators

The water radiator has for purpose to increase the total heat transfer of a system. We decided to include two radiators in our design in order to optimize the overall heat transferred to the greenhouse. Radiators are an older and simple technology and are thus not that expensive. We estimate that the cost for these radiators is **150 $US.**

Temperature Monitoring System

Finally, the last initial cost associated with our design is the temperature control system. In order for it to work, many parts are necessary. A simple laptop costing 300 $US for the LabView programming is required, assuming the user doesn’t already own one. Secondly, a relay board costing approximately 120 $US is also needs to be connected to the laptop. Thirdly, a water pump and valve are needed to control the flow out of the water tank, this type of equipment would cost 70 $US. Finally, temperature monitoring devices are needed in order to collect the temperature in the greenhouse. These devices need to be electronic in order to transmit data and would cost no more than 80 $US. The total cost for the temperature control system amounts to **570 $US.**

Whole Sale Discount

The prices previously given are if we only wanted to make one system, but in reality if people liked our design we would have to build a lot more than one unit. We assume that the parts will be bought in larger quantities and therefore the supplier should be able to provide a discount rate. Without being too optimistic we estimate that a **discount rate of 20%** is reasonable and it should be applied on all parts.

Installation Cost

Given that we have procured all the parts needed for our design, this system still needs to be built and implemented for the specific greenhouse. This will require labor. Realistically, we estimate that the system can be constructed two 8 hour days by 2 professionals working for 20$US per hour. This will result in a total installation cost of **625 $US**.

Total Initial Cost

Adding up all the cost associated with the material and equipment and with the installation of the system, we obtain a total initial cost of exactly **8576 $US**.

Operational Cost

We assume that the user has too put effort in maintaining and operating our design throughout the year. We also assume that the user has first hand access to a compost manure mixture and to machinery needed to load and unload this mixture from the compost tank. On average, we estimate that the user will have to load and unload 16 different batches of compost (value obtained in later calculations, *Benefits*). We estimate that each operation will require 1.5 hours of labor (at 15$US/hour) and cost 10 $US of equipment usage. In total, we therefore estimate that annual operational costs of **520 $US** are needed for the usage of our design.

Annual Financial Benefits

As calculated previously, our system has the potential to deliver 2275 Joules per second. This energy would otherwise have to be obtained from an external vendor at a certain price. In this section we would like to calculate the annual financial benefits of our design.

Our assumption for the composter heat exchanger, obtained from literature, (Viel et al, 1987) was that the mass of compost will have a heat recovery period of 5 day. In other words, each batch of compost will be able to produce 2275 Watts for 5 days. We estimate that on average, our design will operate 16 times per year. Our system will operate more times in colder moths and less in hotter ones as seen from table 4 on the next page;

	Number of Operations
January	3
February	3
March	2
April	1
September	1
October	1
November	2
December	3

Table 4: Operations per Month

Therefore we can make the following calculation;

$$\mathbf{2275}\left[\frac{W}{batch}\right]*\mathbf{24}\left[\frac{hours}{day}\right]*\mathbf{5}\,[days]*\ \mathbf{16}\left[\frac{batch}{year}\right]=\ \mathbf{4368}\,KWh$$

4368 KWh is the annual saving of using our design. If we assume a price of 0.55 $US for 1 KWh of energy, the annual financial savings will equal **2400 $US** as seen from the following equation;

$$\mathbf{4368}\,[KWh]*\mathbf{0.55}\left[\frac{\$US}{KWh}\right]=\mathbf{2400}\,\$US$$

Payback Period (PP)

The payback period is a financial tool by which we can calculate the time needed to compensate the initial cost of a project. In our design, we found the initial cost, the installation cost, the annual operational cost and the annual financial benefits; we can therefore calculate our project payback period in the following manner;

	Cost	Benefit	Total Cash Flow ($US)
Year 0	8576	0	-8576
Year 1	520	2400	-6696
Year 2	520	2400	-4816
Year 3	520	2400	-2936
Year 4	520	2400	-1056
Year 5	520	2400	824

Table 5: Payback Period

The payback period for our design is **4.4 years**. This means that in only four and a half years, the user would pay off the costs of the system and every year afterwards, he will be profiting at a rate of **1900 $US**.

Further Work:

There is still a lot of further work that can be done on this topic. What we have produced is all the theory behind the process itself. The information and physical parameters where obtained from literature. It would be thus very exciting to put the theory in practice and actually build such a design. With a physical model we can see how the test results vary from those calculated in theory. Also, we believe that by putting the theory to practice, we will encounter difficulties and issues that didn’t account in our theoretical modeling. Hopefully after fixing or correcting these difficulties, we will have an even better understanding of the subject and we could then be able to provide our own data collected to the people interested. We hope that in the near future it would be possible to obtain funds to test a working model. We are very optimistic about the results that a physical representation of our design would produce.

Conclusion

In conclusion, our final design proposal explained in this report is the summation of the work our team has done over the past two semesters. In the first semester we set up the most effective way to gather energy from a composting reaction and use it to heat a greenhouse. In this second semester, we concluded that it would too hard and maybe impossible heat a greenhouse only with our compost heat extraction method. We therefore changed our goal and assumed that our design is only necessary to provide a 3 degree change inside the greenhouse and a 40 degree change in water but we still wanted to establish the optimal way to do so. Overall, we achieved our long set goal and created a design that is feasible both physically and financially in optimizing heat extraction from compost and using it to heat a greenhouse. Our design is self-monitoring, requires minimal inputs of energy and has a relatively short payback period. Our report can be used has a blueprint by anyone who is interested in the process of heating a greenhouse with compost. Our design parameters and part assembly are specific for the greenhouse on Mac campus but they can be can be implemented for space heating almost any greenhouse structure or building.

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Annexe

List of Properties

Pipe Properties (Copper)	
Outside D [m]	0.075
Inside D [m]	0.07
Length [m]	80
Thermal Cond [W/mK]	400

Properties of Water @ 318K (45 C)	
Density [Kg/m^3]	990.2
Specific Heat [J/KgK]	4181
Thermal Cond [W/mK]	0.624
Dynamic Vis [Pa*s]	5.90E-04
Kinematic Vis. [m^2/s]	6.06E-07
Thermal Diffusivity [m^2/s]	1.51E-07
Mass Flow Rate [Kg/s]	0.5

Properties of Air @ 296 K (23 C)	
Density [Kg/m^3]	1.205
Specific Heat [J/KgK]	1005.1
Thermal Cond [W/mK]	0.0257
Dynamic Vis [Pa*s]	0.00001983
Kinematic Vis. [m^2/s]	0.00001511
Pr	0.713
Prw	0.696
Velocity [m/s]	**0.05**

Temperature in Greenhouse [K]	**296**

hi [W/(m^2 K)]	**790.6773**
Reynold's #	1.52E+04
Prandlt #	4.02
Nusselt #	88.69777

ho [W/(m^2 K)]	5.671377
Reynold's #	227.8744
Prandlt #	0.713
Nusselt #	16.55071

Uo [W/(m^2 K)]	5.627919
Temp. Outlet [K]	316.9114
Total q [W]	**2275.621**

hi [W/(m^2 K)]	=	(B12*E13)/B5
Reynold's #	=	((B17/(B10*0.7854*(B5^2)))*B5)/B14
Prandlt #	=	B14/B15
Nusselt #	=	0.023*(E11^0.8)*(E12^0.4)
ho [W/(m^2 K)]		(B22*E19)/B4
Reynold's #		(B28*B20*B4)/B23
Prandlt #		B25
Nusselt #		0.57*(E17^0.49)*(E18^0.37)*((B25/B26)^0.25)
Uo [W/(m^2 K)]		((B4/(E9*B5))+((B4*(LN(B4/B5)))/(2*B7))+(1/E15))^(-1)
Temp. Outlet [K]		B30-((B30-318)*(EXP(((-3.1416)*B4*B6*E21)/(B17*B11))))
Total q [W]		B17*B11*(318-E23)