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GEOTHERMAL HEATING SYSTEM FOR JORDANIAN GREENHOUSES

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ABSTRACT

Protective cultivation is widely used nowadays in order to increase crop yield by creating the optimum conditions such as temperature, humidity and CO_2 content, irrespective of outside conditions. Since plant production doubles for every 10 degrees increase in temperature to a certain limit, this makes temperature a very important factor for optimum plant growth. In order to keep the greenhouse temperature constant during changes in outside conditions, heating and often cooling are required.

Heating of a greenhouse can be done using different systems and design procedures. In this report two methods were used for calculating the heating load required, the first method (static method) includes calculations of heat losses due to infiltration and conduction through the greenhouse cover at a single design point, which is the minimum outside temperature. It also assumes the greenhouse to be empty with no plants in it. This method also disregards moisture transfer and assumes air to be dry. The second method is rather complicated and requires computer simulation but it incorporates all energy and mass transfer to the greenhouse and gives results based on true outside conditions. A comparison between the results of the two methods was made. It was clear that the simple method in greenhouse heating design with a 10% safety factor can be used with sufficient accuracy and, thus, the use of complex relations are not needed.

1. INTRODUCTION

By definition a greenhouse is a structure covering ground for growing a crop that will return a profit to the owner risking time and capital (Hanan, 1998). From this definition it is understood that a greenhouse is used for overcoming climatic adversity, where favourable conditions for optimum crop growth are created inside the greenhouse environment without any concern for changes in outside climate conditions.

Although greenhouses provide a protected environment for crops, they themselves are in contact with the outside environment, which leads to energy transfer between the inside and the outside of the greenhouses. Hence, in order to keep the inside conditions approximately constant against varying outside conditions, the greenhouses have to be heated, cooled and ventilated depending on outside climatic conditions. Since the primary aim of protected cultivation is to increase profits by improving product quality and increasing crop yield, the climate control system must be as cheap and as reliable as possible.

Heating a greenhouse can be performed using different systems and energy sources, such as fossil fuels and geothermal energy. Each of these energy sources has its advantages and disadvantages in the greenhouse heating system. Heating systems utilizing fossil fuels might have low initial cost, but their running costs are high, as well as causing pollution to the environment. On the other hand geothermal energy heating systems might have high initial costs but low running costs and are pollution free which makes these systems highly attractive to farmers.

In this project a geothermal heating system was designed for a typical Jordanian greenhouse. Then a computer simulation of the heated greenhouse was made in order to further understand the response of the greenhouse to changes in outside conditions and whether the heating system used can cope with these changes and maintain the desired conditions.

2. GEOTHERMAL GREENHOUSE HEATING SYSTEMS

Often the choice of type of heating system is not dictated by engineering considerations, such as use of available geothermal resource or even the most economical system, but on grower preference, which may be based on past experience. It may also be influenced by factors such as the type of the crop, or potential disease problems. All the factors above should be considered in order to choose the proper heating system. The following paragraphs outline the performance of the different heating systems used in greenhouse heating.

2.1 Finned pipe

A finned pipe is usually constructed of steel or copper pipe with steel or aluminum fins attached to the outside wall. These fins can either be circular, square or rectangular in shape. In the size range employed in greenhouses, a steel pipe with steel fins is most common.

Finned elements are generally installed along the long dimension of the greenhouse adjacent to the outside wall (Figure 1). Improved heat distribution is achieved if about one-third of the total required length is installed in an evenly spaced pattern across the greenhouse floor. This system has the disadvantage of using precious floor space that would otherwise be available for plants. In addition, it is less capable of dealing effectively with ventilation if required. Maintenance requirements are low, particularly if a heat exchanger is used. In addition the natural convection nature of the finned pipe system does not increase electrical costs as a result of the fan operation.

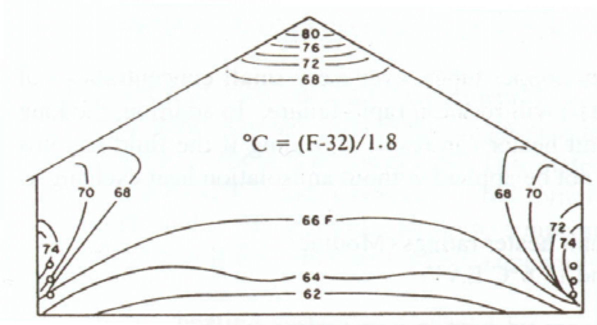


FIGURE 1: Temperature profiles in a greenhouse heated with radiation piping along the side walls (Lund, 1996)

The heat output capacity per meter length of finned pipes is generally rated at 93°C average water temperature, and 18°C entering air temperature. The lower the water temperature inside the pipes the lower the heat output from these pipes which makes them unfeasible at low geothermal temperatures.

2.2 Standard unit heaters

Unit heaters consist of a finned coil and small propeller fan contained in a pre-designed unit (see Figures 2 and 3). These units are available in either horizontal or vertical configurations and are generally hung from the greenhouse structure at roof level. Air is discharged either directly into the greenhouse or into a perforated plastic distribution tube. As with the finned pipe system, unit heaters are generally rated at 93°C entering water temperature and 16°C entering air temperature. Changes in either of these two parameters will affect unit capacity.

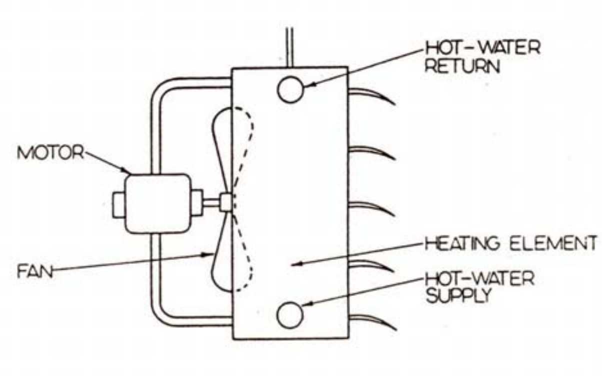


FIGURE 2: Horizontal hot water unit heater (Lund, 1996)

Since most geothermal resources used for greenhouse heating are less than 93°C, some adjustments of unit capacity is needed, usually bigger sizes are needed to achieve the desired load.

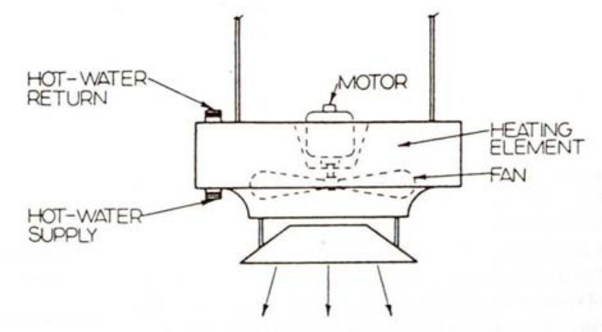


FIGURE 3: Vertical hot water unit heater (Lund, 1996)

Another disadvantage is that these units are constructed with copper tubes, so that even small concentrations of dissolved hydrogen sulfide (H_2S) or ammonia (NH_3) will result in rapid failure. In addition, the long path through which the water flows in the unit heater can result in scaling if the fluid has this tendency. As a result, a unit heater system should always be used in a closed loop system where the unit heaters are never in contact with the geothermal water.

2.3 Fan coil units

These units are very similar to standard unit heaters discussed previously. They consist of a finned coil and a centrifugal blower in a single cabinet. A few manufacturers offer units in an off-the-shelf line for low-temperature greenhouse heating. It is much more common that they are custom selected. The difference between the fan coil unit and hot-water unit heater is primarily in the coil itself. In the fan coil system, the coil is much thicker and usually has closer fin spacing than the coil in a unit heater. Unit heaters generally have only one or two coil rows. A custom designed coil can have as many as six or eight rows. The added surface area allows for more effective heat transfer, resulting in the ability to extract more heat from the water.

2.4 Soil Heating

This system uses the floor of the greenhouse as a large radiator to supply the heat needed by the greenhouse. Tubes, through which warm water is circulated, are buried in the floor of the greenhouse. Heat from the warm water is transferred through the tube to the soil and eventually, to the air in the greenhouse.

In the past, tube materials were generally copper or steel. But due to corrosion and expansion problems with these materials, non-metallic materials have been used more extensively in recent years. The most popular of these is polybutylene. This material is able to withstand relatively high-temperatures (up to 82°C) and is available in roll form for easy installation while PVC and Polyethylene piping are limited with respect to temperature.

A soil heating system is preferred by many growers since it results in very even temperature distribution from floor to ceiling and does not obstruct floor space or cause shading. However, its ability to cover 100% of the heating load of a greenhouse is limited to a rather mild climate and a low inside design temperature. This is caused by the nature of heat transfer in the system. As heating requirements are increased, the required heat output from the floor is increased, and in order to produce more heat, the floor surface temperature must be increased. Very quickly a point is reached at which it is difficult to spend extended periods on such a hot floor. In addition, if plants are grown on or near the floor surface, heat transfer to the plants may be excessive with a radiant floor system. This problem is illustrated in Figure 4. As a result this system is generally employed in conjunction with another system such as unit heaters. Another disadvantage of this system is its slow response to sudden climatic changes, which increases danger to crops being cultivated.

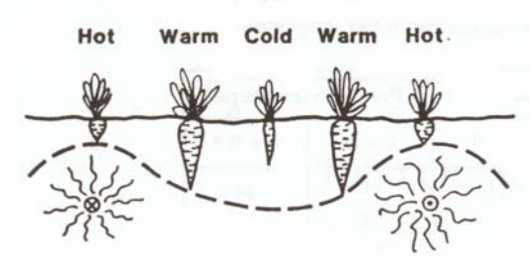


FIGURE 4: Idealized effect of temperature on carrots (Lund, 1996)

2.5 Cascading

This method which was developed by the Soviets for waste heat applications, involves distributing water over the outside of the greenhouse in a thin sheet of flow. Although this is a very effective method of heating a greenhouse, there are some disadvantages that would limit its use in geothermal applications. Distributing large quantities of warm water over a surface exposed to the atmosphere results in substantial energy losses. These losses exceed by many times the requirements of the greenhouse. As a result of the large heat losses from the cascaded fluid, a great deal of evaporation takes place.

Because of the many chemical species contained in geothermal fluids, evaporation would tend to cause high concentration and subsequent deposits of these constituents on greenhouse surfaces.

2.6 Bare tube system

This system involves the use of bare tubing, usually small diameter polybutylene or similar material. The tubing is installed either on the floor or suspended under benches. It is preferable for the tubing to be located low in the greenhouse, although a portion may be located overhead. Regardless of the installation location, it is very important that the tubing be arranged such that each tube is separated from the others. If the tubes are bunched together, the effective surface area of each is reduced, thus lowering the heating capacity.

This system has the problem of requiring large quantities of tubing in order to meet 100% of the heating load. Control of the system may be manual via gate valves. However, as with the soil heating system, the use of heat exchangers can allow accurate control of the temperature and hence the output.

2.7 Bare pipe system

In many locations such as Iceland, China and Hungary, bare steel pipes are commonly used, placed along the outer walls of the greenhouse. The pipes are typically 2 inches in diameter and consist of up to six or eight runs hung on each side with U-bend reversals in a continuous loop. Geothermal water and even two-phase flow is circulated directly through these pipes with the heat being transferred into the space by natural convection. Small shell-and-tube heat exchangers are connected to the system to provide warm water for cleaning and plant watering, since cold watering water may cause thermal root shock. This heating system appears to be more successful than the finned pipe system as the fins may clog with dirt and plant material which reduces their efficiency in heat transfer.

3. STATIC DESIGN PROCEDURE

3.1 Heating load requirements

In order to select a heating system for a greenhouse, the first step is to determine the peak-heating requirement for the structure. Heat loss for a greenhouse is composed of two components: (a) transmission losses through the walls and roof, and (b) infiltration and ventilation losses caused by the heating of cold outside air.

Transmission heat losses calculation
To evaluate transmission losses, the first step is to calculate the surface area of the structure of the greenhouse. This surface area should be subdivided into the various materials employed, i.e. square meters of polyethylene, square metres of fiberglass, etc. After that the transmission heat loss is calculated using the following equation:

$$Q_t = UA(T_i - T_o) \tag{1}$$

where

Q_t = Heat transmission losses through walls and roof [W];
U = Heat transfer coefficient [W/m^2°C];
A = Surface area [m^2];
T_i = Indoor design temperature [°C];
T_o = Outdoor design temperature [°C].

The value of the heat transfer coefficient (*U*), depends on wind speed. Hence, using Table 1, a correlation between the *U* factor and wind speed was found in order to use it in the program.

TABLE 1: Heat transfer coefficient values (W/m^2 °C), at various wind speeds, V (Rafferty, 1998)

Material	**V = 0 (m/s)**	**V = 2.24 (m/s)**	**V = 4.47 (m/s)**	**V = 8.94 (m/s)**	**V = 11.18 (m/s)**	**V = 13.41 (m/s)**
Glass	4.34	5.40	5.91	6.47	6.59	6.70
Fiberglass	3.95	4.91	5.39	5.87	6.01	6.12
Single poly	4.60	5.68	6.19	6.76	6.87	6.98
Double poly	3.04	3.58	3.83	4.07	4.13	4.18

Infiltration heat loss calculation
For greenhouse design, infiltration is generally analysed via the air change method. This method is based upon the number of times per hour (ACH) that the air in the greenhouse is replaced by cold air leaking from outside. The number of air changes which occur is a function of wind speed, greenhouse construction, and inside and outside temperatures. Table 2 outlines general values for different types of greenhouse constructions, which can be used by the designers.

TABLE 2: Air change data for different glazing materials (Rafferty, 1998)

Greenhouse cover material	ACH
Single glass	2.5 - 3.5
Double glass	1.0 - 1.5
Fiberglass	2.0 - 3.0
Single polyethylene	0.5 - 1.0
Double polyethylene	0.0 - 1.0
Single polyethylene with low fiberglass sides	1.0 - 1.5
Double polyethylene with low fiberglass sides	0.5 - 1.0
Single polyethylene with high fiberglass sides	1.5 - 2.0
Double polyethylene with high fiberglass sides	1.0 - 1.5

After selecting the appropriate number from above, it is necessary to calculate the volume of the structure, then Equation 2 is used to calculate the infiltration heat losses:

$$Q_i = V \times ACH \times C_p \times \rho \times (T_i - T_o) / 1000 \qquad (2)$$

where

Q_i = Infiltration heat losses [W];
V = Volume of greenhouse [m^3];
ACH = Air change per hour (from Table 2);
C_p = Specific heat capacity of air [J/kg°C];
ρ = Density of air [kg/m^3];
T_i = Indoor design temperature [°C];
T_o = Outdoor design temperature [°C].

By addition of transmission and infiltration heat losses we get the total heat loss of the greenhouse as shown in Equation 3:

$$Q_{TOTAL} = Q_t + Q_i \qquad (3)$$

After calculating the maximum required heating load for the greenhouse, we can choose the adequate system to heat the greenhouse. If unit heaters or fan coil units were chosen, only the devices with the required capacities are to be selected from the manufacturers' catalogues and installed in the greenhouse. As for soil and bare tube heating systems, further calculations are needed in order to complete the design of these heating systems. These calculations are presented in the following chapters.

3.2 Soil heating system design

The procedure for designing a floor system consists of:

a) Determining the heat load for the greenhouse;
b) Calculating the required floor temperature to meet the load;
c) Calculating the required size, depth and spacing of the tubes.

While the determination of the heat load was covered in Chapter 3.1, the next step is to determine the required floor surface temperature in the greenhouse. The heat output of the floor is a function of the floor surface temperature, greenhouse air temperature and average temperature of unheated surfaces in the room. Heat output from the floor occurs by two mechanisms, convection and radiation. After the heat loss of the greenhouse has been calculated, it is divided by the area of the greenhouse floor which will be used for heating purposes. This gives the required q/A (W/m^2) needed to be supplied by the floor surface to cover for the heat loss. Equation 4 (Lund, 1996) is used to calculate the required floor surface temperature.

$$\frac{q}{A} = 0.472[(\frac{1.8T_p + 492}{100})^4 - (\frac{1.8AUST + 492}{100})^4] + 2.186(T_p - T_o)^{1.32} \tag{4}$$

where

q/A = Heat/Area [W/ m^2];
T_p = Floor surface temperature [°C];
T_a = Indoor air temperature [°C];
$AUST$ = Average temperature of unheated surfaces in the greenhouse (walls and roof) [°C].

Furthermore

$$IST = IDT - (0.0291 \times 3.6 \times U \times \Delta T) \tag{5}$$

where

IST = Inside surface temperature [°C];
IDT = Inside design temperature [°C];
U = Glazing material heat loss factor [W/ m^2 °C];
DT = Design temperature difference (inside - outside) [°C];

and

$$AUST = \frac{A_1 \times IST_1 + A_2 \times IST_2 + \ldots\ldots\ldots\ldots + A_n \times IST_n}{A_1 + A_2 + \ldots\ldots\ldots + A_n} \tag{6}$$

where

A = Surface area of glazing material [m^2].

By solving Equation 4, the floor temperature (T_p) can be determined.

At this point the designer should check whether this temperature is too hot for the plants or for the workers in the greenhouse, and if the soil heating system should be used to cover only a fraction of the total load or if it can cover the total load. After determining the required soil surface temperature, the next step is to determine the depth and spacing of the tubes needed to meet this requirement. Generally, the depth is more a function of protecting the tubes from surface activity than system design. It is commonly 5-15 cm below the surface. Since it is the purpose of the floor panel system to use the floor as a large radiator, it follows that the installation of the tubing should result in as uniform a floor surface temperature as possible. This can be accomplished in two ways: (a) placing smaller diameter tubes at close spacing near the surface of the floor, or (b) placing larger tubes spaced further apart at deeper levels (Lund, 1996).

At this point the designer should know the heating load required, the floor surface temperature, heating water temperature and burial depth, which is a function of protecting the tubes from surface activity. After that, and using Equation 7 (Björnsson, 1980), the designer has to decide the size and length of pipes needed to supply the necessary heating load.

$$L = \frac{Q \times \ln[(8(\frac{H}{d})^2 - 1) + 4(\frac{H}{d}) \times \sqrt{4(\frac{H}{d})^2 - 1}]}{4 \times \pi \times \lambda_j \times t_m} \tag{7}$$

where

Q	=	Heating load [W];
L	=	Pipe length [m];
H	=	Pipe burial depth (floor surface to pipe center) [mm];
d	=	Pipe outside diameter [mm];
λ_j	=	Earth heat conductivity [W/m°C];
t_m	=	Log mean temperature difference [°C];

and

$$t_m = \frac{(T_i - T_o)}{\ln(\frac{T_i - T_s}{T_o - T_s})} \tag{8}$$

where

t_m	=	Log mean temperature difference [°C];
T_i	=	Water inlet temperature [°C];
T_o	=	Water outlet temperature [°C];
T_s	=	Floor surface temperature [°C].

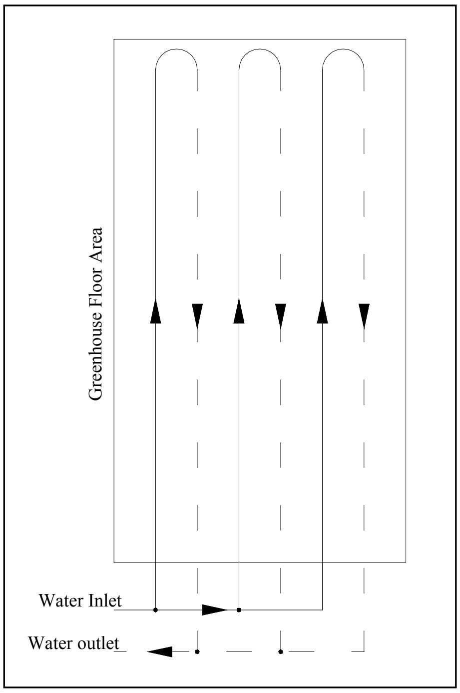


FIGURE 5: Heating pipe distribution inside a greenhouse

From Equation 7, it is seen that the length of the heating pipe depends on many variables, most of which cannot be controlled by the designer, but are functions of location and construction of the greenhouse. Where the pipe burial depth is a function of surface activity and plants' location within the greenhouse, heating load is a function of the construction of the greenhouse. Water inlet temperature is a function of the geothermal field from which the water is being taken. The designer can only decide the pipe diameter and water temperature drop across the loop, and then get the length of the pipe needed to cover the load required.

In order to have a homogeneous temperature distribution, the pipes are arranged parallel to the greenhouse length, Figure 5. After determining the length of the pipe, the number of pipes (n), is determined by

$$n = \frac{L_{pipe}}{L_{greenhouse}} \tag{9}$$

where

n	=	Number of pipes;
L_{pipe}	=	Pipe length [m];
$L_{greenhouse}$	=	Greenhouse length [m].

3.3 Bare tube system design

As described in Chapter 2.6, this system involves installing bare polybutylene tubes, or similar material, on the floor of the greenhouse. The tubes are arranged in such a way that each tube is separated from the others. Otherwise if the tubes were bunched together, the effective surface area of each is reduced, thus lowering heating capacity.

The first step in designing this heating system is of course to determine the heating load, but that was done in Chapter 3.1. Next the designer has to determine the temperature drop across the loop, which is usually between 10 and 20°C. Knowing the heating water inlet temperature, which is determined by the geothermal field, the temperature drop and the heating pipe diameter, determined by the designer, the heating pipe length can be calculated according to Equation 10 (Lund, 1996):

$$L = \frac{3.6Q}{[4.422\times(\frac{1}{D})^{0.2}\times(\frac{1}{1.8T_{ave}+32})^{0.181}\times(\Delta T)^{1.266} + 15.7\times10^{-10}[(1.8T_1+32)^4-(1.8T_2+32)^4]\,]11.345A} \quad (10)$$

where

L	=	Pipe length [m];
Q	=	Heating load [W];
D	=	Outside diameter of tubing [mm];
T_{ave}	=	$255.6 + (AWT + T_{air})/2$ [°C];
AWT	=	T_i - $DT/2$ [°C];
T_i	=	Heating water supply temperature [°C];
T_{air}	=	Greenhouse design air temperature [°C];
DT	=	$AWT - (T_{air}+3)$ [°C];
T_1	=	$255.6 + AWT$ [°C];
T_3	=	$(AUST + T_{air}) / 2$ [°C];
T_2	=	$255.6 + T_3$ [°C];
A	=	Outside surface area of pipe/unit length [m^2/m].

As in the soil heating system, the two variables that the designer has real control over are the temperature drop across the loop, and the pipe diameter.

3.4 Peaking with fossil fuels

There are certain cases in which it is not feasible to design the geothermal heating system to cover 100% of the load, instead peaking equipment using fossil fuels are used to cover the peak load, while the geothermal system is used to cover a base load. The rationale behind different base load and peak load heating systems lies in the annual temperature profile, where the base load, using geothermal energy, might be designed to cover 50-70% of the peak load, and it will still meet up to 90% of the annual heating energy requirements. Figure 6, shows percentage of annual heating energy vs. peak load percentage covered by the heating system for south Amman area in Jordan.

From Figure 6 it is seen that if the base load heating system was designed to cover 70% of the peak load, it will still meet 90% of the annual heating energy required. The following chapters explain the calculations used in determining the capacities of two peaking systems, air heaters and boilers.

3.4.1 Peaking with air heating equipment

Sizing an air heating peaking equipment procedure is rather simple; the capacity of this equipment (W) is the peak (W) load minus the base load (W) covered by a bare tube or soil heating system.

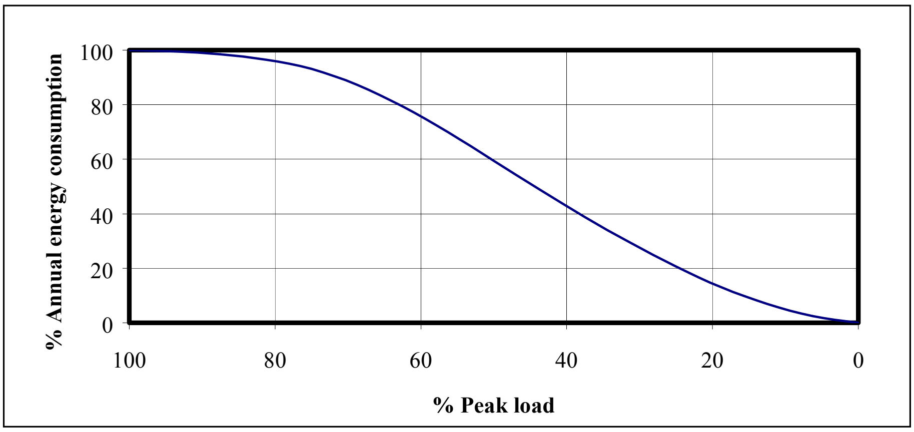


FIGURE 6: Annual heating energy requirements

$$Heating\ equipment\ capacity = Peak\ load - Base\ load \tag{11}$$

3.4.2 Peaking with a boiler

Calculating the capacity of the heating boiler needed to cover the peak load is not as simple as the air heating equipment calculations above. The boiler increases the supply water temperature, which not only influences the output of the terminal equipment, but also the capacity of the geothermal heat exchanger (refer to Figure 7). As the supply water temperature rises, the output of the terminal units rises. At the same time, the return water temperature rises as well, and if the loop configuration is as shown in Figure 7, the geothermal heat source capacity to increase the return water temperature is greatly reduced. In some extreme cases, the return water temperature from the heating loop might be higher than the temperature of the geothermal water temperature, which implies that the boiler has to cover the total load. This is best illustrated by an example.

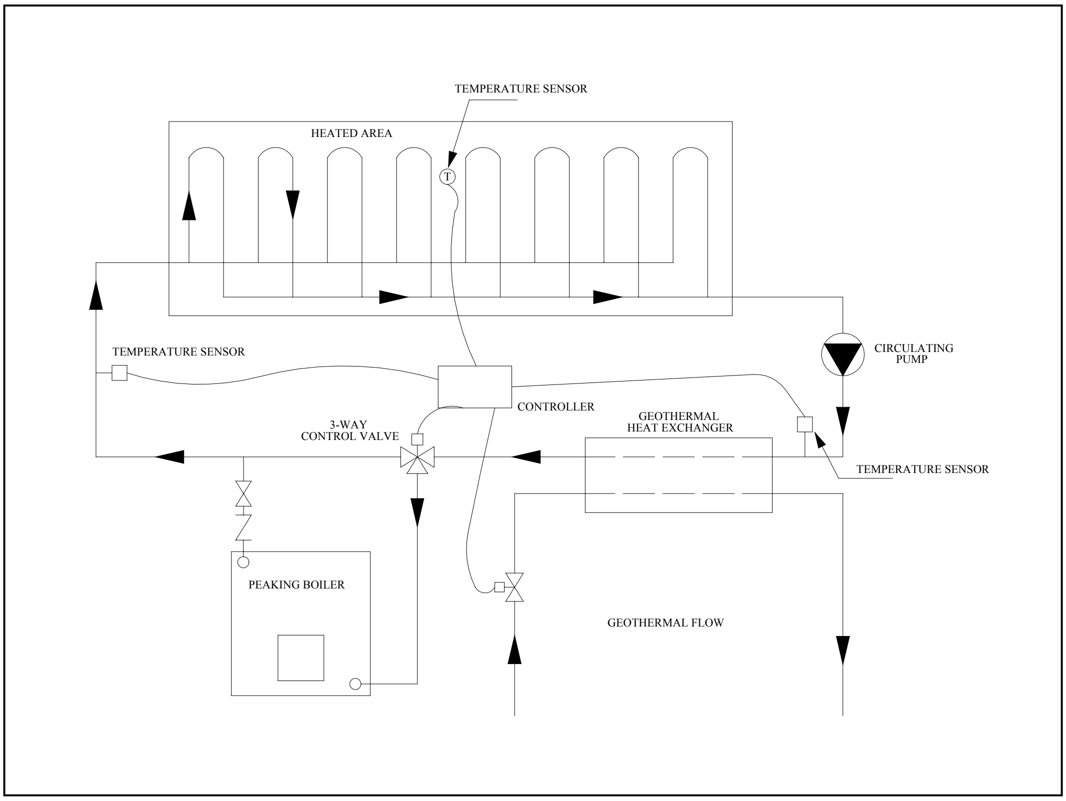


FIGURE 7: Peaking system flow diagram

In the example below the total load is about 400 kW, and the geothermal heating system is used to cover 280 kW (base load). The remaining load is covered by a boiler peaking system. All the data relative to the example is given below:

Peak load	=	400 kW
Base load	=	280 kW
Geothermal water temp.	=	60 °C
Heat exchanger loss	=	3 °C
Loop water return temp.	=	15 °C
Loop water flowrate	=	4.46 kg/s
Pipe length	=	8525 m (Equation 10)

From the data given in this example, notice that the base load is used to cover 70% of the peak load, and at 280 kW, the heat output per metre length from the pipes is

$$q/l = 280{,}000/8{,}525 = \mathbf{32.8\ W/m}$$

At peak load, the length of the pipes, and loop water flowrate cannot be changed, hence the heat output from the pipes must be increased to cover the increase in heat loss. So, the new heat output per metre length of pipes is

$$q/l = 400{,}000/8{,}525 = \mathbf{46.9\ W/m}$$

In order to achieve this higher output the supply water temperature must be increased. In order to estimate this new temperature Equation 10 is solved, where the only unknown is the average water temperature (*AWT*). After determining *AWT*, the temperature drop across the heating loop can be determined from Equation 12.

$$\Delta T = AWT - (T_{air} + 3) \tag{12}$$

where

ΔT	=	Temperature drop across the heating loop [°C];
AWT	=	Average water temperature in the heating loop [°C];
T_{air}	=	Greenhouse design air temperature [°C].

After determining the temperature drop and using Equation 12 the new supply water temperature, T_i, can be determined as follows:

$$T_i = AWT - \Delta T/2 \tag{13}$$

and the return water temperature, T_r as

$$T_r = T_i - \Delta T \tag{14}$$

By solving Equations 10, 12, 13 and 14, the following results are obtained:

AWT	=	**61.1 °C;**
DT	=	**21.4 °C;**
T_I	=	**71.8 °C;**
$\mathrm{T_r}$	=	**50.3 °C.**

From the initial data, it is known that the geothermal heat source raised the loop water temperature from 42 to 57°C at 280 kW load. At 400 kW load, the heating loop return water temperature is 50.3°C. The geothermal heating source will raise the temperature of the water only to 57°C, i.e. by seven degrees instead of fifteen, so the contribution of the geothermal system is decreased. Hence, the boiler has to cover for this decrease by adding more heat to the water to increase its temperature from 57 to 71.8°C.

$$Boiler\ capacity = m \times C_p \times \Delta T \tag{15}$$

where

Boiler Capacity	=	Boiler heating capacity [kW];
m	=	Loop water flowrate [kg/s];
C_p	=	Specific heat capacity of water [kJ/kg °C];
ΔT	=	Temperature change across the boiler [°C].

Hence *Boiler capacity* = 4.42 × 4.186 × (71.77 - 57) = **275.75 kW**

From this result it is seen that even though the base load covers 70% of the total load, the boiler capacity needed is 68% and not 30% of the total load.

4. THE DESIGN PROGRAM

From the discussion above, it is seen that the designer has many options and needs to do a lot of calculations and solve many equations in order to properly design and optimize a greenhouse heating system. To make calculations easier, an EXCEL spread sheet program was written to help the designer reduce time and effort in designing a proper heating system for a greenhouse.

The program 'DESIGN', is an EXCEL worksheet that calculates the greenhouse heating load, gives the design output for soil and bare tube heating systems, as these are the two systems that need complex calculations. A description of the program is given on the following pages. In order to make it as general as possible, the program is based on a geothermal heating system layout as shown in Figure 8, where it is assumed that there is a heat exchanger between the geothermal water and the heating loop. Such a system is widely used, and needs more calculations than the case with no heat exchanger.

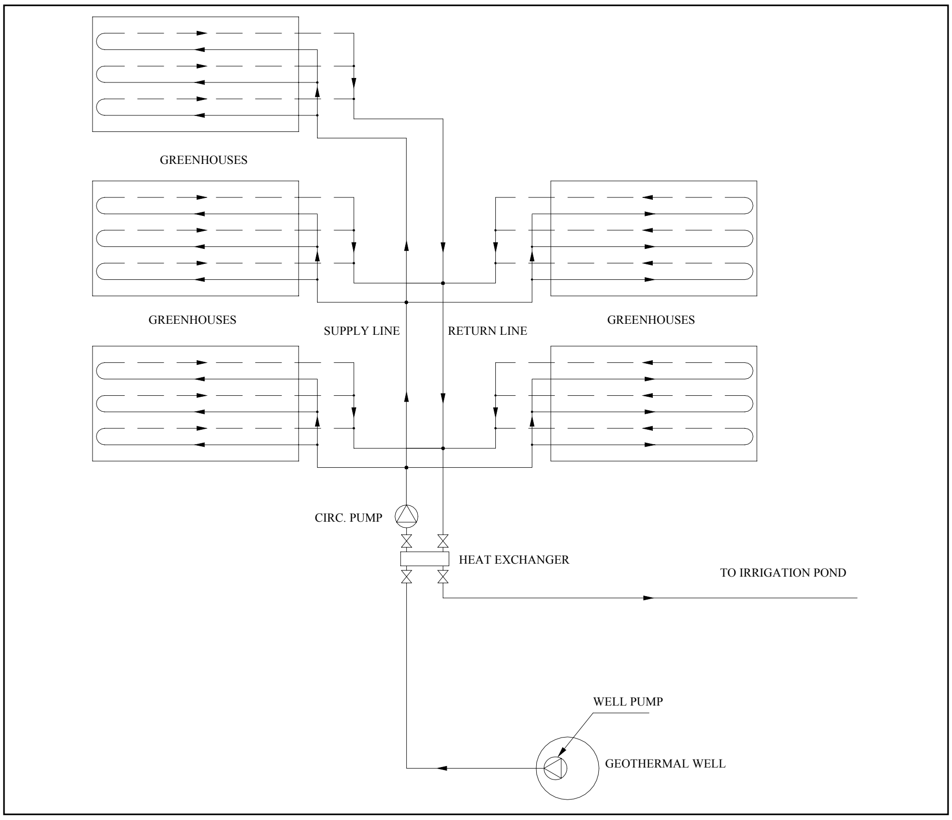


FIGURE 8: Geothermal heating system layout

1-	**Weather data**		**2-**	**Greenhouse data**	
a-	Outdoor Design Temp. (C)	0,00	a-	Greenhouse Length (m)	56,00
b-	Indoor Design Temp. (C)	16,00	b-	Greenhouse Width (m)	45,00
c-	Wind Speed (m/s)	7,00	c-	Side Walls area (m^2)	0,00
d-	Air Density (kg/m^3)	1,10	d-	Side Walls Cover Material	**3**
e-	Air Cp (kJ/kg K)	1,02	e-	Roof area (m^2)	3450,00
			f-	Roof Cover Material	**3**
3-	**Heating data**		g-	Front Wall area (m^2)	120,00
			h-	Front Wall Cover Material	**3**
a-	Hot Water Temp. (C)	40,00	i-	Back Wall Area (m^2)	120,00
b-	Heat Exchanger dt (C)	0,00	j-	Back Wall Cover Material	**3**
c-	max. soil temp (C)	26,00	k-	Greenhouse Volume (m^3)	6720,00
			l-	Infiltration Rate (ACH)	**1,0**
			4-	**Heating systems data**	
			a-	Soil U value (W/m^2K) **(4.26)**	4,26
			c-	Tube K value (W/m K)	1,30
			d-	Tube Inside Diameter (mm)	29,10
			e-	Tube Outside Diameter (mm)	32,00
			f-	Tube Depth Surface to pipe center (cm)	15,00
			g-	Loop Water Temp. Drop (DT) **(10)**	15,00
			h-	Header Inside Diameter (mm)	48,00

FIGURE 9: Data input sheet of the DESIGN program

4.1 Data input sheet

The first sheet of the program, the data input sheet, is where the designer assigns the design parameters and provides the necessary data for the calculations in the following sheets. Figure 9 shows the data input sheet. From the figure, the data required is divided into four categories:

a) Weather data, which provides the outdoor design temperature, indoor design temperature, wind speed, air density and C_p;
b) Greenhouse data, provides information about the greenhouse components' properties;
c) Heating data. This category provides data about the geothermal water available, the temperature drop across the heat exchanger, if used, and the maximum allowable soil temperature for the soil heating system;
d) Heating system data. In this category the designer puts his design options, such as pipe diameter, burial depth and temperature drop across the loop.

The data provided in a) and b) is used for calculating the heating requirements of the greenhouse under study. The data from c) and d) is used in soil and bare tube system design, sheets three and four.

The cover material type is characterized by numbers, because the program automatically calculates the heat transfer coefficient (*U*), depending on the cover material and wind speed, where

1 = Glass cover	2 = Fiberglass cover
3 = Single polyethylene cover	4 = Double polyethylene cover

A-	Transmission Heat Loss			
	Greenhouse Part	**Area (m^2)**	**U (W/m^2 K)**	**Heat Loss (kW)**
1-	Roof	3450.00	6.56	362.17
2-	Side Walls	0.00	6.56	0.00
3-	Front	120.00	6.56	12.60
4-	Back	120.00	6.56	12.60
			TOTAL	**387.36**

B-	Infiltration Heat Loss			
	Air Change / hr.	**Volume (m^3)**	**Outside air flow (L/s)**	**Heat Loss (kW)**
	1.00	6720.00	1866.67	33.51
			TOTAL	**33.51**

C- Total Heat Loss **420.87 (kW)**

D- Total Greenhouse Area **2520 (m^2)**

Please Enter the Total Heat Loss in the marked Box **420.87** **kW**

FIGURE 10: Heating load calculations sheet

4.2 Heating load calculations

After entering the data input sheet, the program automatically calculates the heating load requirements of the greenhouse and the data is displayed as in Figure 10.

4.3 Soil heating system design sheet

The third sheet of the program displays the soil heating system design results, but as stated in Chapter 3 the designer should use the solver tool in order to solve Equation 4 above, for the surface floor temperature. After that all the design results are displayed for different peak load fractions.

Figure 11 shows the soil heating system design sheet, where the solver tool in the EXCEL program is used on the row labeled (*dq/a*), where its value should equal zero by manipulating the value of Soil Temp in the second row. Looking at Figure 11, it is notable that there are no results for 100% and 90% of the peak load. As can be seen from Figure 8, this is because the geothermal water temperature was 40°C, and the temperature drop across the loop was 15°C, hence loop water outlet temperature would be 25°C, while the needed soil temperature is 27.88˚C, which is higher than the loop outlet water temperature. Hence, the designer needs to decrease the temperature drop across the loop in order for this system to work.

4.4 Bare tube heating system design

In this sheet the design results of the bare tube heating system are displayed. Also the heating capacities of peaking equipment are displayed for several fractions of the peak load, where the geothermal system is used to cover a certain base load, and the other equipment covers the peak load. The results are shown in Figure 12.

% Load	100	90	80	70	60	50
Load (kW)	420.87	378.79	336.70	294.61	252.52	210.44
Soil Temp (C)	**27.88**	**26.44**	**24.96**	**23.42**	**21.82**	**20.13**
Pipe Depth (cm)	15.00	15.00	15.00	15.00	15.00	15.00
Pipe Outside Diameter (mm)	32.00	32.00	32.00	32.00	32.00	32.00
Pipe Heat Output (W/m)	#NUM!	#NUM!	7.12	17.79	24.01	29.77
Total Pipe Length (m)	#NUM!	#NUM!	52054.58	18211.79	11569.84	7774.47
Pipe Spacing (m)	#NUM!	#NUM!	0.05	0.14	0.22	0.32
Loop Water Inlet Temp (C)	40.00	40.00	40.00	40.00	40.00	40.00
Loop Water Outlet Temp (C)	25.00	25.00	25.00	25.00	25.00	25.00
Loop Water Flow Rate (kg/s)	6.70	6.03	5.36	4.69	4.02	3.35
Air Heating equipment cap. (kW)	**0.00**	**42.09**	**84.17**	**126.26**	**168.35**	**210.44**
Geothermal Water Inlet Temp (C)	40.00	40.00	40.00	40.00	40.00	40.00
Geothermal Water outlet Temp (C)	25.00	25.00	25.00	25.00	25.00	25.00
Geothermal Water Flow Rate (kg/s)	6.70	6.03	5.36	4.69	4.02	3.35
Unheated Sufaces Temp. (C)	5.20	5.20	5.20	5.20	5.20	5.20
dq/a (=0 USING SOLVER)	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
NOTES	**TOO HOT**	**TOO HOT**	**OK**	**OK**	**OK**	**OK**

FIGURE 11: Soil heating system design sheet

% Load	100	90	80	70	60	50
Load (kW)	420,87	378,79	336,70	294,61	252,52	210,44
Pipe Outside Diameter (mm)	32,00	32,00	32,00	32,00	32,00	32,00
Pipe Heat Output (W/m)	17,81	17,81	17,81	17,81	17,81	17,81
Total Pipe Length (m)	25993,87	23394,49	20795,10	18195,71	15596,32	12996,94
Pipe Spacing (m)	0,09	0,10	0,11	0,13	0,15	0,18
Number of loops	232,09	208,88	185,67	162,46	139,25	116,04
Loop Water Inlet Temp (C)	40,00	40,00	40,00	40,00	40,00	40,00
Loop Water Outlet Temp (C)	25,00	25,00	25,00	25,00	25,00	25,00
Loop Water Flow Rate (kg/s)	6,70	6,03	5,36	4,69	4,02	3,35
Loop Water Velocity (m/s)	0,04	9,11	8,10	7,09	6,08	5,06
Total Pressure Drop (m)	0,09	0,08	0,08	0,08	0,08	0,08
Geothermal Water Inlet Temp (C)	40,00	40,00	40,00	40,00	40,00	40,00
Geothermal Water outlet Temp (C)	25,00	25,00	25,00	25,00	25,00	25,00
Geothermal Water Flow Rate (kg/s)	6,70	6,03	5,36	4,69	4,02	3,35
Air Heating Equip. Cap. (kW)	**0,00**	**42,09**	**84,17**	**126,26**	**168,35**	**210,44**
Unheated Sufaces Temp. (C)	5,20	5,20	5,20	5,20	5,20	5,20

PEAKING USING A BOILER						
Average Water Temp. (C)	**32,50**	**34,18**	**36,23**	**38,79**	**42,09**	**46,54**
Pipe Heat Output (W/m)	17,81	19,79	22,26	25,44	29,68	35,62
dq (using solver = 0)	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**
New Supply Water Temp (C)	40,00	42,51	45,60	49,50	54,59	61,54
New Water Return Temp. (C)	25,00	25,85	26,85	28,08	29,59	31,54
Flow Rate (kg/s)	6,70	6,03	5,36	4,69	4,02	3,35
Boiler Capacity (kW)	0,00	63,47	125,79	186,68	245,70	302,21
Boiler % of Total Load	**0**	**15**	**30**	**44**	**58**	**72**

FIGURE 12: Bare tube heating system design

5. PROJECT DESIGN

5.1 Greenhouses in Jordan

Most greenhouses used in Jordanian protected agriculture are Quonset type with the following specifications:

Length	=	56 m;
Width	=	9 m;
Height	=	3.2 m;
Cover material	=	Single polyethylene.

These greenhouses are locally manufactured, which makes them cheap and simple to maintain, hence their use is very attractive to farmers. Since this greenhouse type is the most commonly used in Jordan, five greenhouses of this type will be used in the heating system design presented here.

5.2 Project site and choice of plants

The site chosen for this project lies in the southern part of Amman (capital of Jordan), where the geothermal water is 40-50°C, with a flowrate of 50-60 m^3/hr. Although there are other regions in Jordan which have better geothermal resources, such as the Jordan Valley and north of Amman, this region was chosen for the following reasons:

- The use of water by heavy industry installed in the north of Amman, which considerably reduces the possibilities of downstream irrigation in that area;
- The large water outputs needed for irrigation and cooling in the Jordan Valley;
- The pollution of groundwater in those regions.

Hence, the south of Amman area plays an increasingly important role in agriculture. The ground water is of good quality for irrigation, and the climate is neither too hot in the summer nor too cold in the winter.

The plants chosen for the project are roses. This is due to several reasons. The internal temperature required for optimum growth of roses is 16°C, while it is 22°C for cucumbers and tomatoes, hence less energy is needed to heat greenhouses with roses. Finally, earnings from roses are higher than those of vegetables.

5.3 Design parameters and results

From the above-mentioned information, the basic information needed to start designing a geothermal heating system can be acquired and is summarized in Table 3.

TABLE 3: Design parameters for geothermal heating system

Parameter	**Value**
Indoor design temperature	16°C
Outdoor design temperature	0°C
Geothermal water temperature	40°C
Greenhouse cover material	Single polyethylene cover
Greenhouse length	56 m
Greenhouse width	9 m
Greenhouse height	3.2 m
Air changes for the greenhouse	1.0 *ACH*

In Chapter 2, a detailed discussion of greenhouse-heating systems was introduced, and their advantages and disadvantages were discussed. Yet the selection of one or a combination of two or more systems depends on several factors, such as type of crop being grown, availability of energy sources and economic evaluation. In this project the bare tube heating system was chosen because of the geothermal resources' low-temperature. The system is also simple and does not require maintenance, which is ideal for Jordanian agriculture.

As discussed in previous chapters, there are many parameters affecting the required heating loop length. In order to design a good heating system, it is necessary to understand how these parameters affect the loop length. This is discussed in the following chapters.

5.3.1 Effect of temperature drop across the loop and inlet water temperature on loop length

Figure 13 shows the effect of temperature drop across the heating loop (dT) and inlet water temperature on the required pipe length. The indoor temperature and pipe diameter are assumed to be constant. It clearly shows that the influence of dT increases significantly as the inlet water temperature decreases. The increase in length between dT = 20°C and dT = 5°C is 27% at 60°C inlet water temperature, and this increase reaches 60% at 40°C.

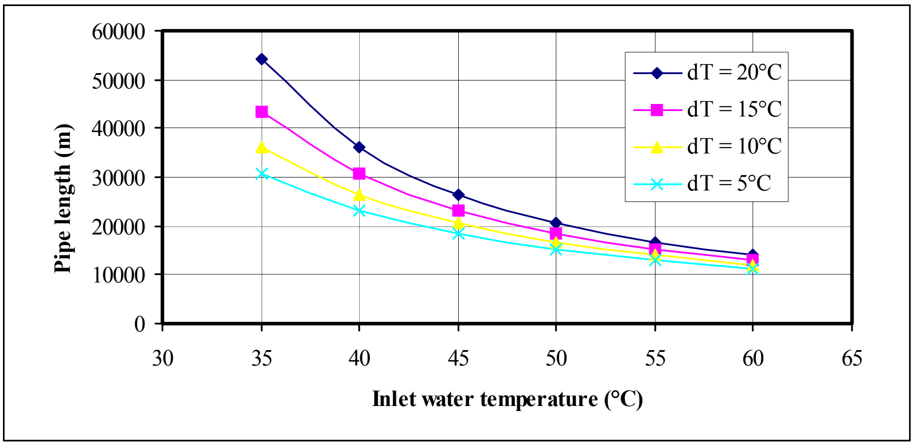


FIGURE 13: Effect of temperature drop (dT) and inlet water temperature on loop length

5.3.2 Effect of heating pipe diameter and inlet water temperature on loop length

The heat transfer from the heating pipe to the atmosphere takes two forms, radiant heat transfer and convective heat transfer. The surface area of the heating pipe affects the rate of heat transfer from the heating fluid to the atmosphere. Figure 14 shows the effect of pipe diameter (D), (surface area), and inlet water temperature on the loop length. It is very clear that the influence of diameter is quite significant. The figure shows that by changing the diameter from 32 to 20 mm, an increase of about 50% in pipe length is required to cover the same load. The pipe diameter is not greatly affected by the inlet water temperature, as in the temperature drop case. Whereas changing the pipe diameter from 32 to 20 mm yields an increase of loop length of 53% at 60°C, this percentage increases only to 57% at 40°C inlet water temperature.

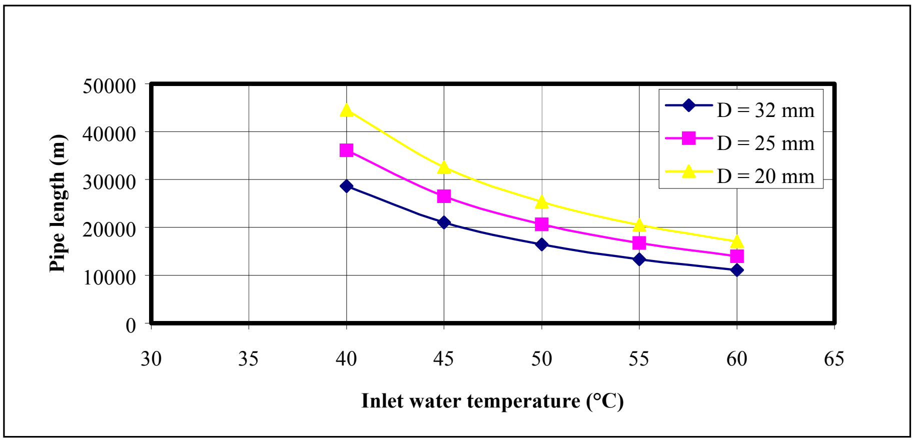


FIGURE 14: Effect of pipe diameter and inlet water temperature on loop length

5.3.3 Effect of temperature drop across the loop on flowrate

Another factor that should not be disregarded is the heating water flowrate, which is mainly limited by the geothermal well capacity, water availability and abundance. In Jordan water is scarce and preserving it is of great importance. Figure 15 shows the effect of temperature drop on the water flowrate. It clearly shows that temperature drop has a tremendous effect on flowrate, which must be considered during the design. It is seen that at a temperature drop of 20˚C the flowrate is only 5 kg/s, while decreasing the temperature drop to 5˚C the flowrate need to be increased to 20 kg/s.

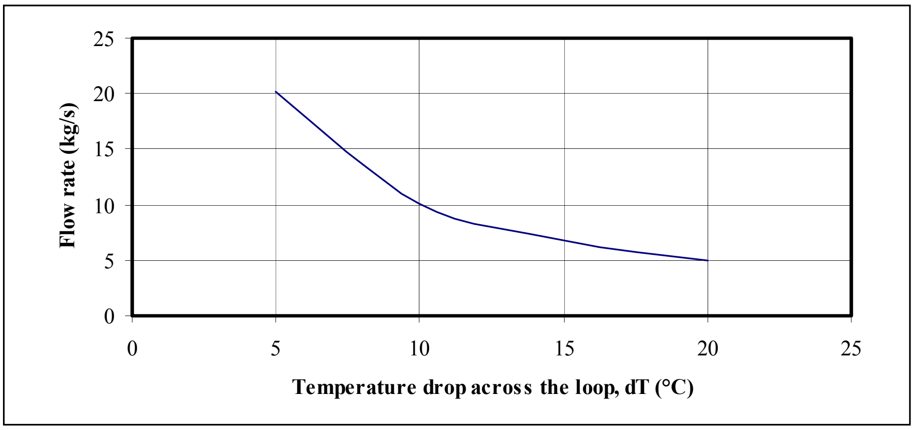


FIGURE 15: Effect of temperature drop across the loop on flowrate

5.4 Geothermal heating system design options

After studying the effects of the various design parameters on the design output, and using the DESIGN program for getting the needed results, the final decision is left to the designer who should take into consideration the costs, as well as the space available in the greenhouse, and water consumption. The different options along with their costs are shown in Table 4.

TABLE 4: Geothermal heating systems options, assuming 40°C water inlet temperature

Option number	Load (kW)	Temperature drop (°C)	Water flow rate (kg/s)	Pipe diameter (mm)	Pipe length (m)	System cost ($)
1	421	15	6.7	20	40241	58500
2	421	15	6.7	25	32709	54171
3	421	15	6.7	32	25994	52308
4	421	20	5.0	20	48053	70170
5	421	20	5.0	25	39010	64606
6	421	20	5.0	32	30959	63500

Cost calculations include pipes, fittings and installation costs (from Jordanian market prices)

Although option 6, from Table 4 above, is not the cheapest, it was chosen because of space considerations and a water conservation point of view.

6. SYSTEM SIMULATION

In the static design, it was assumed that the outside conditions do not change, the greenhouse was empty with no crops inside, and the calculations were based on dry air only and no attention was paid to the water vapour. Also the heat loss calculations included only transmission and infiltration heat losses, while the only heat gain to the greenhouse was considered to be the heating system. However this is not really the case, because outside conditions change with time, the greenhouse is full with crops, water vapour affects the heat transfer calculations, and as shown in Figure 16 there are more heat losses and gains in greenhouses, than those accounted for in the static calculations.

The aim of the simulation model of the greenhouse is to evaluate the static design assumptions and validate its results, as well as to understand what really happens inside a greenhouse and how the heating system reacts to changes in outside conditions. The following chapters present a discussion of the heat gains and losses included in the simulation model.

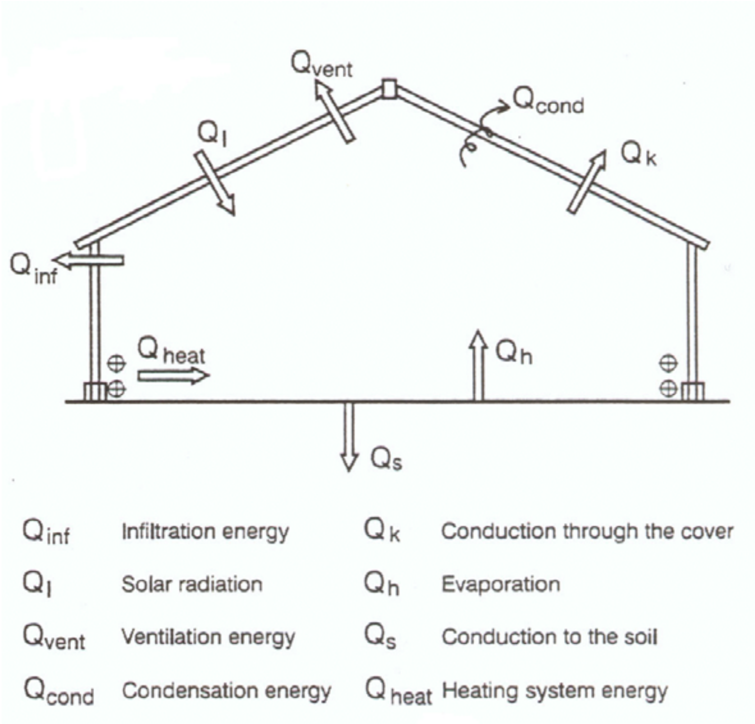


FIGURE 16: Greenhouse heat and mass transfer (Druma, 1998)

6.1 Heat gain sources

The heat gain sources for the greenhouse model discussed here include solar heat gain from the sun, heating system heat gain and heat from condensation of water vapour on the greenhouse cover. Following is a detailed description of each of these heat sources and their contributions to the total heat gain of the greenhouse.

6.1.1 Solar radiation heat gain

Solar radiation is the most determinant factor in greenhouse cultivation. This is because light is needed by the plants to produce food and oxygen by way of photosynthesis and hence, it is the basis of plant survival. Also, glass and other greenhouse cover materials have the property of allowing short wave radiation from very high-temperature bodies such as the sun, to penetrate through them, while they prevent long wave radiation, coming from the plants and soil, from leaving the greenhouse. Hence, the glass is trapping the energy inside the greenhouse causing its temperature to rise.

The fraction of the energy used in photosynthesis is negligible compared to the solar energy used in heating (Hanan, 1998), so it will be neglected in the calculations. Hence, the energy entering the greenhouse is calculated according to the following relation:

$$Q_s = I \times \tau \times \gamma \times A_g \qquad (16)$$

where

Q_s = Useful solar energy entering the greenhouse [W];
I = Total outside solar energy falling on a horizontal surface (obtained from meteorological data), [W/m^2];
A_g = Area of greenhouse floor, [m^2];
τ = Light transmission of greenhouse cover for solar radiation; $\tau = 0.8$ (Kimball, 1996);
γ = Constant of the proportion of solar radiation entering the greenhouse, useful to increase internal temperature; γ is in the range 0.3-0.7; a value of 0.3 was chosen.

6.1.2 Heating system heat gain

The heating system chosen consists of bare tubes laid on the greenhouse floor. The heat loss from these pipes to the greenhouse environment is calculated according to the following equation:

$$Q_{hs} = m \times C_p \times (T_{wi} - T_{wo}) \qquad (17)$$

where

Q_{hs} = Heat gain from the heating system [W];
m = Heating water flow rate [kg/s];
T_{wi} = Heating water inlet temperature [°C];
T_{wo} = Heating water outlet temperature [°C];
C_p = Specific heat capacity of water [J/kg K].

All the parameters are constant except T_{wo}, which is calculated according to the following equation:

$$T_{wo} = (T_{wi} - T_{in}) \times e^{-kL/mC_p} + T_{in} \qquad (18)$$

where

T_{in} = Greenhouse ambient temperature [°C];
k = Pipe convection heat transfer coefficient [W/m K];
L = Loop pipe length [m];

6.3 Heat gain due to condensation

Condensation is the transformation of water from vapour phase to liquid phase, where the air temperature is below a certain value called the dew point. At this point the air can no longer carry all the water vapour particles and water vapour begins to condense. In the greenhouse, condensation takes place on the greenhouse cover only when the cover's temperature is lower than the dew point temperature of the inside air. Upon condensation, water releases energy of about 2.45×10^6 J/kg of condensed water; this is the latent heat of condensation which is released from the water vapour to the greenhouse environment.

In order to calculate the heat gain from condensation, the following formula (Hanan, 1998) is used:

$$Q_{cond} = C \times L_v \times A_c \qquad (19)$$

where

Q_{cond} = Heat gain from condensation [W];
C = Water condensation rate on the cover [kg/s m^2];
L_v = Latent heat of condensation = 2.45×10^6 [J/kg];
A_c = Greenhouse cover surface area [m^2].

C can be calculated as follows (Hanan, 1998):

$$C = \frac{A_c}{A_f} 1.64 \times 10^{-3} (T_{vin} - T_{vc})^{1/3} (X_{ain} - X_c) \qquad (20)$$

where

A_f = Greenhouse floor area [m^2];
T_{vin} = Inside air virtual temperature [°C];
T_{vc} = Greenhouse cover virtual temperature [°C];
X_{ain} = Inside absolute humidity [kg/ m^3];
X_c = Cover absolute humidity [kg/ m^3].

The virtual temperature of the air inside the greenhouse and the cover temperature can be estimated according to the following equations:

$$T_{vin} = \frac{T_{in}}{1 - \frac{e_{ain}}{P} \times (1 - \varepsilon)} \tag{21}$$

where

e_{ain} = Vapour pressure of the air inside the greenhouse [Pa];
P = Atmospheric pressure [Pa];
ε = Ratio of the molecular weights of water and air = 0.622;

and

$$T_{vc} = \frac{T_c}{1 - \frac{e_{ain}}{P} \times (1 - \varepsilon)} \tag{22}$$

where

T_c = Cover temperature [°C].

The cover temperature, on the other hand, is calculated using the following formula (Lund, 1996):

$$T_c = T_{in} - (0.0291 \times 3.6 \times U \times (T_{in} - T_o)) \tag{23}$$

where

U = Heat transfer coefficient [W/m^2 K].

U is calculated according to the following equation:

$$U = 3.351 \times 10^{-5} \times W^5 - 1.269 \times 10^{-3} \times W^4 + 0.019 \times W^3 - 0.140 \times W^2 + 0.707 \times W + 4.340 \tag{24}$$

where

W = Wind speed [m/s].

Equation 24 was derived from Table 1 of this report.

X_c is calculated according to the following equation:

$$X_c = \frac{\rho_a \varepsilon e_{ac}}{P - e_{ac}}$$

where

e_{ac} = Vapour pressure at the cover [Pa];
ρ_a = Density of air = 1.292 kg/m^3;

and e_{ac} is calculated as follows:

$$e_{ac} = RH_c \times e_{sc} \tag{26}$$

where

e_{sc} = Saturation vapour pressure at the cover temperature [Pa];
RH_c = Relative humidity at cover temperature; at condensation its value should be 100%.

The saturation vapour pressure is calculated using the following equation:

$$\ln e_{\sin} = 57.96 - \frac{6731.0}{T} - 4.796 \times \ln T \tag{27}$$

where

T = Cover temperature [K].

6.2 Greenhouse heat loss sources

Heat losses from a greenhouse include losses due to plant transpiration, infiltration of outside air, ventilation losses, heat loss to the soil and transmission heat losses from the greenhouse cover. Below is a description of the mathematical equations used in the model for calculating these losses.

6.2.1 Transpiration

Transpiration is assumed to occur from substomatal cavities in the leaves of vegetation and/or from below the soil surface, where the heat production from this process can be estimated according to the formula (Hanan, 1998):

$$Q_t = H_t \times LAI \times A_g \tag{28}$$

where

Q_t = Heat loss from transpiration [W];
H_t = Latent heat exchange due to transpiration [W/m^2];
LAI = Leaf area index; for a full canopy covered floor LAI = 4.0; it represents the amount of vegetation in the greenhouse;
A_g = Greenhouse floor area [m^2].

H_t can be calculated according to the following formula (Hanan, 1998):

$$H_t = \frac{\rho \times C_p}{\gamma_1 \times r_v} \times (e_{\sin} - e_{ain}) \tag{29}$$

where

H_t	=	Latent heat exchange due to transpiration [W/m^2];
ρ	=	Density of air [kg/m^3];
C_p	=	Specific heat capacity of air [J/kg K];
γ_1	=	Psychrometer constant, which, along with the slope of the saturated vapour pressure curve, is considered a weighing factor that determines the partitioning of the radiant energy between evaporation (latent heat) and convection (sensible heat). For simulation, it is a table-defined variable [Pa/°C];
r_v	=	Resistance of leaves and stomata to heat transfer (m/s), considered constant. For the simulation program it was assumed for roses to be 2400 (Hanan, 1998, Table 5-33);
e_{sin}	=	Saturation vapour pressure inside the greenhouse [Pa];
E_{ain}	=	Actual vapour pressure inside the greenhouse [Pa].

The saturation vapour pressure (e_{sin}) can be calculated using the following formula:

$$\ln e_{\sin} = 57.96 - \frac{6731.0}{T} - 4.796 \times \ln T \tag{30}$$

where T = Temperature [K];

and,

$$e_{ain} = \frac{X_{ain} \times P}{X_{ain} + \varepsilon \rho_a} \tag{31}$$

where

X_{ain}	=	Mass of vapour per unit volume of air inside the greenhouse [kg/m^3];
P	=	Atmospheric pressure [Pa];
ε	=	Ratio of molecular weights of water and air, 0.622;
ρ_a	=	Density of dry air = 1.292 kg/m^3.

Finally X_{ain} is given by

$$X_{ain} = \frac{M_{wt}}{V} \tag{32}$$

where

M_{wt}	=	Mass of vapour per unit volume of the air inside the greenhouse [kg/m^3];
V	=	Greenhouse volume [m^3].

6.2.2 Infiltration heat loss

Infiltration is the entrance of outside air to the greenhouse structure through the structure's cracks and openings. This movement is stimulated by the difference in partial pressures between the inside and outside climates. The value of the infiltration heat loss can be calculated using the following formula:

$$Q_{inf} = [(C_p(T_{in} - T_o) + L_v \Delta q) \rho V_{ginf}] A_c \tag{33}$$

where

Q_{inf} = Infiltration heat loss [W];
ρ = Density of air [kg/m^3];
C_P = Specific heat capacity of dry air [J/kg K];
T_{in} = Greenhouse inside temperature [°C];
T_o = Outside temperature [°C];
L_v = Latent heat of vaporisation = 2.45 x 10^6 J/kg;
Δq = Specific humidity difference, inside to outside, [kg/kg] moist air;
V_{ginf} = Volume air exchange per unit cover area [m^3/m^2 s].

V_{ginf} is calculated as follows:

$$V_{ginf} = \frac{0.44\,W + 0.14\sqrt{(|T_{in} - T_o|)}}{3600} \tag{34}$$

where W = Wind speed [m/s].

As for the specific humidity difference (*Dq*), it is defined as follows:

$$\Delta q = Q_{in} - Q_{out} \tag{35}$$

Also *q* is calculated by

$$q_{in,\,out} = \frac{0{,}622\,e_{ain,aout}}{P - e_{ain,aout} + 0.622\,e_{ain,aout}} \tag{36}$$

where

e_{aout} = Vapour pressure outside the greenhouse [Pa];
e_{ain} = Vapour pressure inside the greenhouse [Pa];

and

$$e_{aout} = e_{sout} \times RH_{out} \tag{37}$$

where

RH_{out} = Relative humidity outside the greenhouse structure, from meteorological data.

6.2.3 Ventilation heat loss

Ventilation is the entrance of outside air into the greenhouse volume by means of mechanical action, where outside air is forced inside by means of fans. Ventilation is used to reduce the greenhouse's temperature as it exceeds the set point. The volume flowrate of the ventilation is controlled via a motorized damper, which controls the opening in front of the fans where the opening area is controlled using a PI control.

The infiltration heat loss is calculated as follows:

$$Q_{vent} = (C_P(T_{in} - T_o) + L_v \times \Delta q)\,\rho_a F_v \tag{38}$$

where

Q_{vent} = Ventilation heat loss [W];
F_v = Volumetric air flow due to ventilation [m^3/ s].

6.2.4 Heat losses to the soil

Heat losses from the greenhouse environment to the soil can be measured by

$$Q_s = U_s \times A_s \times (T_{in} - T_s) \tag{39}$$

where

Q_s = Heat loss to the soil [W];
U_s = Soil heat transfer coefficient [W/m^2°C];
A_s = Soil surface area [m^2];
T_{in} = Greenhouse inside temperature [°C];
T_s = Soil temperature [°C].

As for the soil temperature, it can be calculated as follows:

$$T_s = \int dT_s \tag{40}$$

This is the integral of the soil temperature with time at a given initial condition, where the dT_s is calculated using the following relation:

$$dT_s = \frac{Q_s}{A_s \times D_s \times C_{Ps}} \tag{41}$$

where

D_s = Soil depth [m];
C_{Ps} = Specific heat capacity of soil = 3000 J/kg K.

6.2.5 Transmission heat losses

Transmission heat losses (gains), are losses (gains) through the cover of the greenhouse to (from) the surroundings. The governing equation for calculating this value is given in Equation 1.

6.3 Vapour balance inside the greenhouse structure

Water vapour can be transferred to or from the greenhouse structure by transpiration, infiltration, ventilation and condensation. The net amount of water vapour inside the greenhouse structure can be calculated according to the following equation (Hanan, 1998):

$$D_{tot} = D_{inf} + D_{vent} + D_t + D_{cond} \tag{42}$$

where

D_{tot} = Total water vapour change inside the greenhouse [kg/s];
D_{inf} = Water vapour change due to infiltration [kg/s];
D_{vent} = Water vapour change due to ventilation [kg/s];

D_t = Water vapour change due to transpiration [kg/s];
D_{cond} = Water vapour change due to condensation [kg/s].

D_{inf} and D_{vent} are calculated by

$$D_{inf,\,vent} = (F_{inf} + F_v) \times (X_{ain} - X_{aout}) \tag{43}$$

where
F_{inf} = Air flow due to infiltration [m^{3}/s];
F_v = Air flow due to ventilation [m^{3}/s];
X_{ain} = Mass of vapour per unit volume of the air inside the greenhouse [kg/m^3];
X_{aout} = Mass of vapour per unit volume of the air outside the greenhouse [kg/m^3].

F_{inf} is defined by

$$F_{inf} = V_{ginf} \times A_c \tag{44}$$

and X_{aout} can be obtained from the following relation (Hanan, 1998):

$$X_{aout} = \frac{\rho_a \varepsilon E_{aout}}{P - e_{aout}} \tag{45}$$

The amount of water vapour transferred due to evaporation from plants is given by

$$D_t = \frac{Q_t}{h} \tag{46}$$

where
Q_t = Heat loss from transpiration [W];
h = Enthalpy of moist air [J/kg].

The amount of water vapour transferred due to condensation can be estimated as follows:

$$D_{cond} = C \times A_c \tag{47}$$

where
A_c = Cover surface area [m^2];
C = Water condensation rate on the cover (from Equation 20, above) [$kg/s\ m^2$].

As the equations above give the rate of change of water vapour over time, the total amount of water vapour can be obtained by integrating these amounts over time. Hence

$$M_{wt} = \int_0^t D_{tot}\,dt \tag{48}$$

where M_{wt} = Total amount of vapour exchanged through the greenhouse.

6.4 Greenhouse inside temperature and controllers

After determining the mathematical relationships governing the heat and mass transfer between the greenhouse and its environment, the inside temperature of the greenhouse can be calculated according to the following:

$$\frac{dT_{in}}{dt} = \frac{Q_{total}}{V \times \rho C_P} \tag{49}$$

where

dT_{in} = Rate of change of inside temperature with time [°C/s];
Q_{total} = Total heat transfer to the greenhouse [W];
V = Greenhouse volume [m^3];
ρC_P = Volumetric heat capacity of dry air, 1200 J/m^3 K.

According to Johnson (1967), control is the organization of activity for some purpose, i.e. for holding certain important variables constant in time. There are many kinds of controllers available, which vary in complexity and accuracy in keeping a certain variable constant with time. The type of controller selected for simulation purposes is a proportional integral controller. The discussion of its characteristics is beyond the scope of this report.

7. SIMULATION RESULTS

7.1 Simulation program

The simulation program used to simulate the greenhouse under study is called Advanced Continuous Simulation Language (ACSL). This is a program used for modeling systems described by time dependant, nonlinear differential equations and/or transfer functions. In other words, the program is used for evaluating transient behaviour of systems. This program has a simple programming language and can simulate both continuous and discrete (control) systems, and satisfies the requirements needed for this study.

7.2 Simulation results

The simulation program was run for a typical winter day in Jordan.

7.2.1 Inside temperature

Figures 17 and 18 show the temperature and relative humidity inside and outside the greenhouse for that day. Notice that the greenhouse temperature is highly affected by outside conditions and follows the outside temperature profile

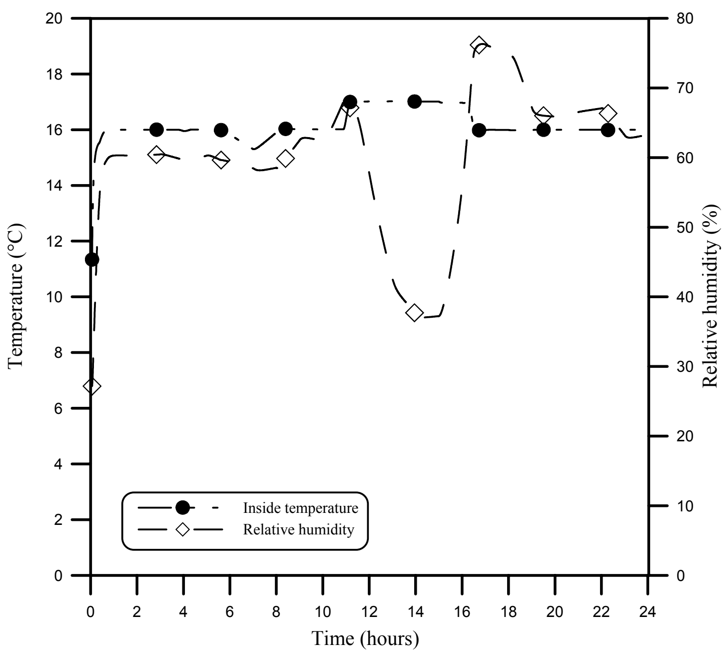


FIGURE 17: Greenhouse inside conditions

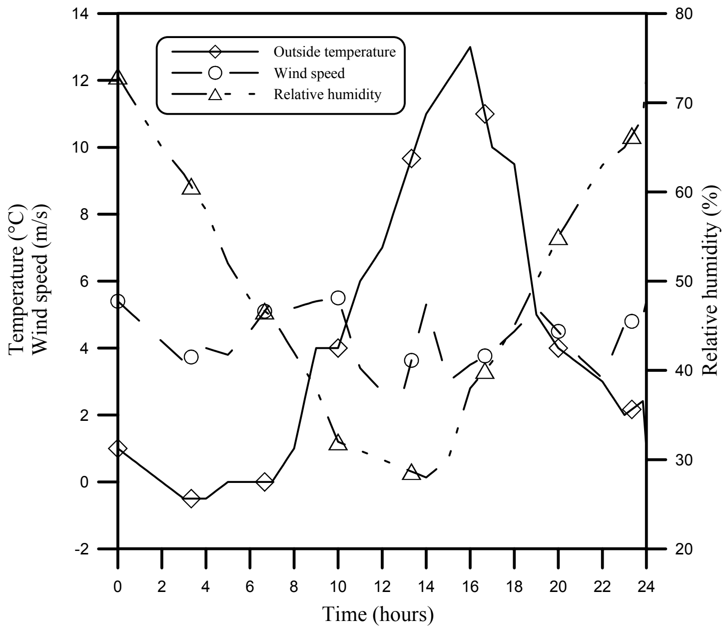


FIGURE 18: Outside weather data

but with a time lag of about half an hour. The outside temperature decreases to below zero at time = 4 hours, while the decrease in the greenhouse temperature does not begin until time = 4.5 hours. Also, as the ambient temperature begins to increase drastically at 10 hours, the increase in greenhouse temperature does not begin until 10.5 hours, but was then stopped by ventilation control.

This is due to the fact that the greenhouse has an inertia, which means that there is a time lag between changes in the ambient conditions and the inside conditions. In this case, the inertia is considered to be small, half an hour. The same applies for the relative humidity which it is highly affected by the outside humidity.

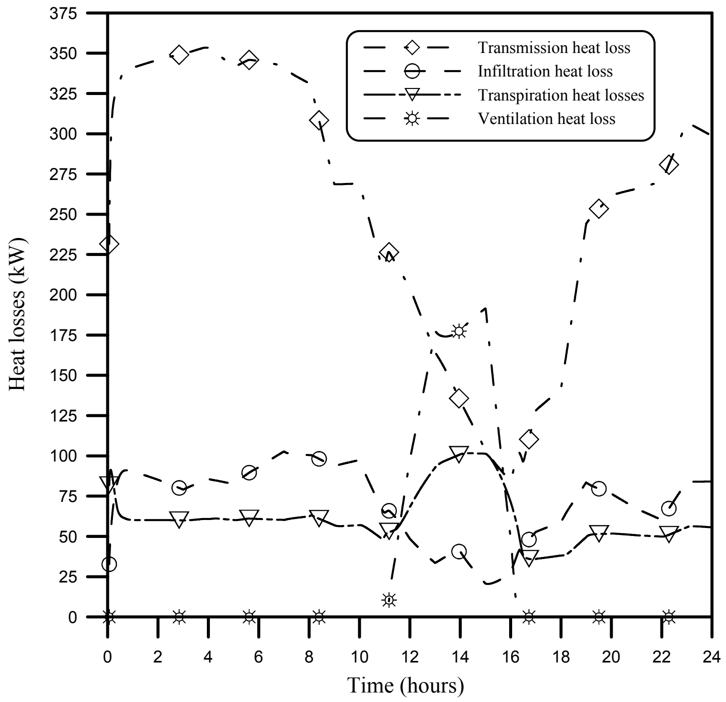


FIGURE 19: Heat losses from the greenhouse

7.2.2 Effects of heat losses

Figure 19 shows the effect of the different heat losses of the greenhouse. It is clear that the transmission heat losses through the greenhouse's cover are the highest. These losses are highly affected by the temperature difference between outside and inside of the greenhouse, where the transmission heat loss is minimum at maximum outside temperature.

As for infiltration heat loss, its value does not exceed 100 kW, and is also reduced by increasing outside temperature. Figure 19 also shows the effect of transpiration heat loss which is a little bit higher than 100 kW. But this heat loss, unlike the other two, increases with increasing outside temperature and solar radiation. Another heat loss shown in Figure 19 is ventilation heat loss. As heat is mechanically generated by the action of fans, it can be controlled by the fans' size and the amount of outside air they can bring in.

Figure 20 shows the heat loss from the greenhouse environment to the soil. It is clear that the value of this heat loss is very small and can be ignored.

7.2.3 Effects of heat gains

As discussed in Chapter 7.1, the heat gain sources of the greenhouse are condensation heat transfer, solar heat transfer and heating system heat transfer. Below is a discussion of the part each plays in the total heat transfer of the greenhouse.

By looking at Figure 20 again, it is clear that condensation heat transfer is quite low, and takes place only when outside temperatures are low. Figure 21 shows both solar and heating system heat gains. It clearly shows that the heating system works at maximum capacity at times when solar radiation is minimal, indicating that solar radiation alone can cover and exceed the heating load of the greenhouse.

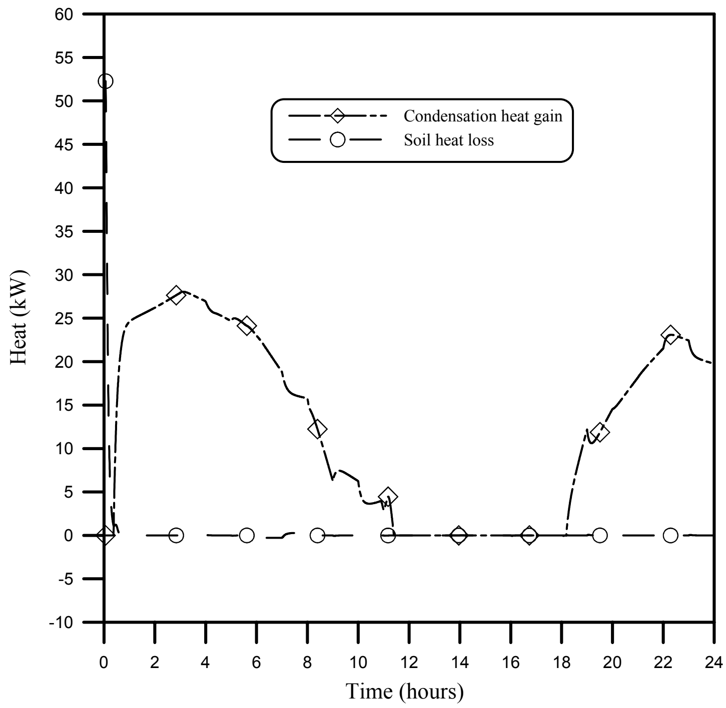


FIGURE 20: Condensation heat gain and soil heat loss simulation results

7.2.4 System's time constant

By definition, time constant means the time needed by a system to reach 67.3% of steady state condition. In this study, a test using the simulation program was made to calculate the heating system time constant in order to evaluate its ability to cope with sudden changes in climate. The test was carried out by stopping the heating system operation for some time, after which the system was allowed to operate and the greenhouse temperature change with time was recorded. Figure 22 shows that the time constant of the system was about five minutes, which is fast and means that this kind of heating system is reliable and can handle sudden changes in outside conditions.

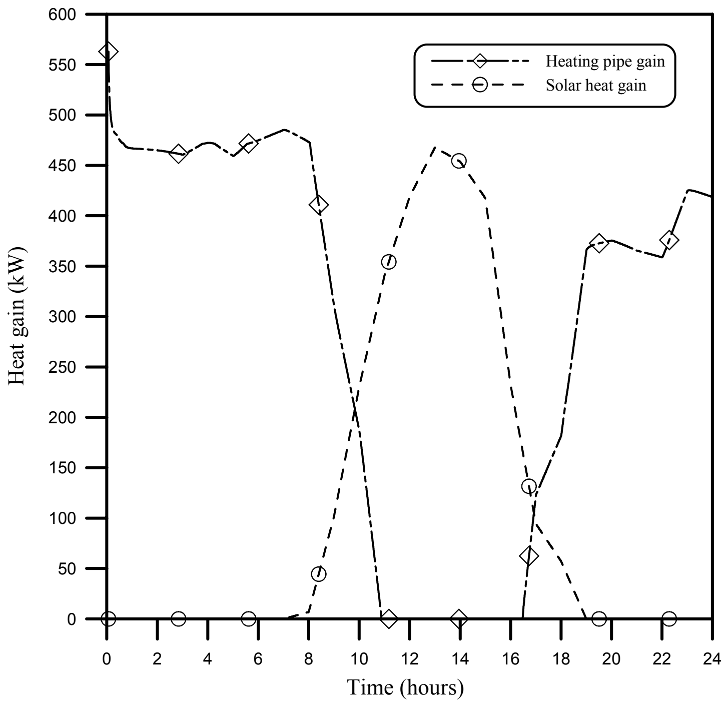
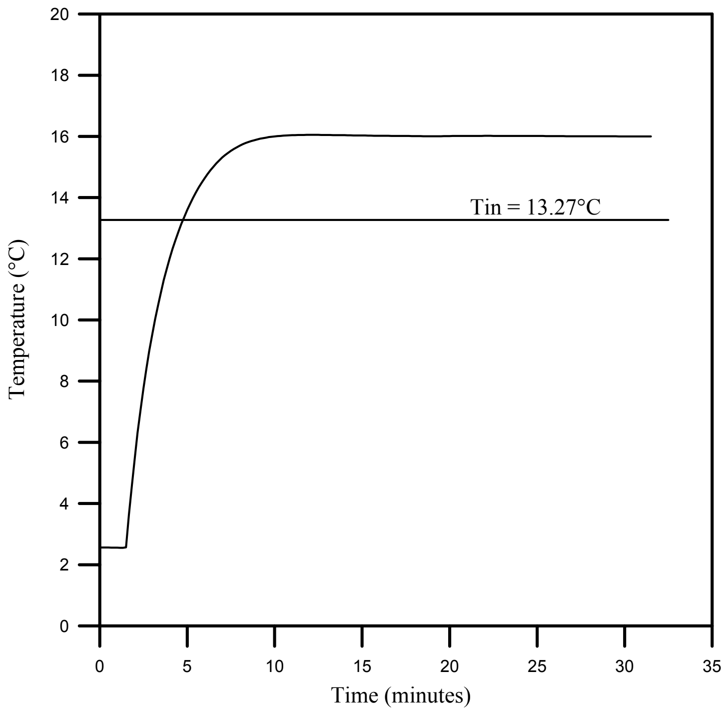


FIGURE 21: Heat gains to the greenhouse

7. CONCLUSIONS

By comparing the static design results with the dynamic design results, it is seen that in the static design the maximum load was 421 kW, while in the dynamic design it was 465 kW. This is due to transpiration heat losses which were not accounted for in the static design. Another reason for this is that the outside temperature was, for some time, below the design temperature.

In the static design, the designer can never accurately predict the system's behaviour or energy and water consumption. Using dynamic simulation, these data can be obtained, which helps the designer optimize



the system and predict its behaviour and weaknesses.

However, it can be stated that the static design method, if design conditions are set at night with no solar radiation included in the calculations, can be used to design a good greenhouse heating system. The design results do not differ much from the dynamic design results. One of the reasons for this is the short time constant of the greenhouse.

Bare pipe heating system has a low time constant and can overcome sudden changes in outside climate provided that hot water is readily available and does not require heating. Where the heat source is geothermal energy, hot water is readily available.

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