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Modeling and simulation of a root-zone heating in greenhouse using solar collectors

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Abstract

Seed germination is often enhanced and accelerated by increasing soil temperature. Researchers have shown interest in heating plant roots in greenhouses, with results indicating that soil heating can improve plant growth, as well as accelerate and enhance both flowering and seed germination in many plant species. Root-zone heating systems can be particularly effective in improving soil bed temperatures in greenhouse environments. A Root-Zone system consists of thermal channels installed to regulate soil temperature. Diesel is often used as fuel for this system; however, due to concerns about fossil fuel depletion and increasing environmental pollution, renewable energy sources are recommended for greenhouse heating. In this research, heat transfer equations related to pipes and solar collectors were modeled using Python software to determine the most optimal configuration. The study aimed to heat a specific type of greenhouse (with an area of 10 m² out of 500 m² in Shahrekord, Iran) using Root-Zone installations. The results indicate that both the diameter and depth of pipe placement significantly affect the amount of heat supplied by the collector. As pipe diameter increases, the required heat for the system rises, and as the pipe depth decreases, the heat supplied from the collector diminishes. Based on these findings, the optimal distance for pipe placement from the roots is 30 cm. Additionally, increasing the water flow speed entering the system reduces the temperature required to heat the roots to the desired level.

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Introduction

Greenhouse agriculture is a growing industry in many countries. Greenhouse systems play a big role in vegetable and global food production (Hu et al., 2021). Energy consumption in the agricultural and greenhouse sectors has always accounted for a large part of the total energy consumption in many countries (Wang et al., 2016). There are various methods for heating greenhouses, including heat exchangers, hot air furnaces, and electric heaters. Typically, the soil is heated by raising the air temperature, but this approach can increase heat loss from the greenhouse and, in some cases, cause damage to the plants. An effective heating system should meet two key criteria: it must be capable of heating the greenhouse during the coldest night of the year and should evenly distribute heat throughout the space. One important factor for enhancing plant growth is maintaining the optimal temperature of the soil bed, which can accelerate the growth and flowering processes of many plants. Additionally, lowering the air temperature while heating the root zone can lead to significant fuel cost savings. Educational and cultivation benefits of using heating systems in greenhouses include faster root growth and respiration, increased crop production over a shorter period, reduced energy loss, and, consequently, lower fuel costs. It's important to note that low root temperatures are a significant limiting factor for horticultural production in temperate regions, particularly during the colder months, a challenge that can be mitigated with the use of root-zone heating systems. Temperature stress below the optimal value usually leads to a decrease in vegetative growth, which may negatively affect fruit yield and quality (Llorach-Massana et al., 2016; Kooli et al., 2015; Xia et al., 2023). In 2014, researchers (Kawasaki et al., 2014) investigated the performance of the tomato crop in two conditions heating the roots and not heating the roots; the results indicated that the product yield was 20% higher and 30.5% heavier according to the root-zone system. Also, there was a significant relationship between the root-zone system and the photosynthesis of the product. The photosynthetic area influences the photosynthetic capacity of plants. Studies have shown that the decrease in root zone temperature (RZT) leads to a decrease in the green leaf area, which leads to a decrease in the photosynthetic capacity and premature senescence of corn (Xia et al., 2023).

The ideal root temperature for other crops has also been investigated. For example, it has already been reported that the suitable root temperature for lettuce production can be between 17 and 24 degrees Celsius. For other crops such as tobacco, cotton, corn, or peas, the ideal root temperature may be 32°C, 25°C, 20°C, and 10°C, respectively. The breeders stated that the soil temperature between 20 and 28 degrees Celsius is optimal for the initiation and growth of soil roots. In general, most farmers have introduced the average temperature of 26 degrees Celsius in the rooting bed as the optimal state (Llorach-Massana et al., 2016; Llorach-Massana et al., 2017)

Currently, direct heating of the soil is considered more economical as it requires less fuel to maintain the same temperature of the soil. Root-zone systems can be useful in improving soil bed heating in greenhouses; a root-zone system consists of thermal channels (pipes containing hot water and electric cables and PCM) installed under the soil to improve the soil temperature. In a root-zone system, any method can be used to increase the temperature of the root part, which are common electric cables and water pipes. Lorach et al. in 2023 found that PCMs are expensive and have a short lifespan, and PCMs are hard to find in the market. Root heating should be considered as a supplement to a greenhouse heating system because it usually does not provide all the heat required by the greenhouse. However, an underfloor heating system may allow the user to lower the nighttime temperature by 5 to 10 degrees Fahrenheit, reducing the overall heating system cost (Lorach et al., 2023).

One of the influential root-zone in the construction and management of the greenhouse is its energy issue and its heating and cooling during the day and night to prevent damage to the plants. Lorach's research results in 2016 (Llorach-Massana et al., 2016) showed that conventional gas, oil, and biomass heating systems cause a net reduction for farmers, so a greenhouse should be designed in such a way as to help profitable businesses in this field by creating the right conditions for the plant. Since temperature is an effective factor in plant growth and the speed of metabolic reactions, plant seeds and roots grow in a certain temperature range in the soil bed. Therefore, by keeping the temperature of the soil bed balanced in a greenhouse system, Thermal problems are inevitable. Today, one of the critical problems for humanity is to reduce the use of fossil fuels to reduce the emission of carbon dioxide (CO2) (Ozdemir, 2023). Burning fossil fuels releases greenhouse gases such as carbon dioxide, nitrogen oxides, particulate matter, and other toxins, all of which affect the local, regional, national, and global climate (Priyadharsini et al., 2022; Rajagopal et al., 2022). In 2023, (AlNemer et al., 2023) stated that without a doubt, climate change is one of the most dangerous threats to human existence and the ecosystem, so in the new decade, researchers should find the cause of pollution to understand the main causes and consequences of climate change. Also, highlight global warming. It is obvious that CO2 emission is one of the main causes of the mentioned problem. Therefore, due to the danger of running out of fossil fuels soon and increasing problems caused by environmental pollution, today, human societies are trying to change their energy supply and demand pattern so that with the advancement of technology, the use of renewable resources as They are a reliable alternative to fossil resources. Renewable energies include diverse and different sources created from natural and accessible energies, considering that using these energies is not common, but their use reduces the consumption of petroleum products. It has created employment and reduced the amount of environmental pollution. In fact, due to the ever-increasing energy price, the need to use renewable energy in heating and cooling greenhouses as cheap and clean energy sources is increasingly rising. Considering the problems in using fossil resources, replacing them with renewable energies is necessary. Meanwhile, solar energy sources have a high share in clean energy production.

Solar technology is a suitable alternative that can be used instead of conventional energy sources (Naveen et al., 2023). Solar energy is reliable, sustainable, and renewable. Although the initial costs involved in the construction and installation of solar cells are high, there is almost no pollution caused by solar panels when installing solar panels. Earth still receives approximately 170,000 TW of solar energy, which could supply approximately 10,000 times the current global energy demand (Lakatos et al., 2011). Rezvani et al. investigated the flat plate solar water heater analysis to estimate reliability and technical-economic benefit. In addition, research was conducted to show the effect of auxiliary/supplementary heating on the economic feasibility of the collector. This study showed that a flat plate solar water heater could provide significant long-term economic feasibility compared to electric water heaters (Rezvani et al., 2017). Following the expansion of the world's population and the increasing need for greenhouses and non-renewable energy, governments are looking for a way to increase greenhouse product production and reduce energy consumption. The root-zone system technology is a way to reduce the amount of energy consumed and increase the fertility of plants. Normally, this system heats the soil bed using non-renewable energies (Llorach-Massana et al., 2017). With the increase in population and the response to the increasing need for food resources, there is no way but to use greenhouses in all seasons, as the highest cost of crop production in the cold season is related to heating. Solar collectors in the greenhouse can reduce the consumption of non-renewable energy (Kooli et al., 2015). Also, by using heat transfer technologies with the help of solar collectors as a unit of heat production, reducing the consumption of non-renewable energy is possible. Water heating based on solar energy is a very good technology that can reduce fossil fuel consumption and carbon dioxide emissions (Chopra et al., 2023).

Most existing resources have focused on PCMs, but PCMs are expensive, have a short lifespan, and are hard to find in the market. In addition, For short-term applications thermal energy storage in Phase Change Materials (PCMs) are usually preferable For biomaterials, it was shown that temperatures can be kept within desired levels for six hours using PCMs (Beyhan et al., 2013). In this case, the heat needed by the roots is not provided on cloudy days and at night, in other words, they are not reliable, But thermal channels such as pipes in different sizes are easily found in the market and are cheap, so the farmer can easily equip the greenhouse with a Root-zone system at a lower cost. It is true that the use of underground pipes requires a lot of equipment, but this system has the ability to be controlled, in other words, it can be easily turned off in the summer, or by using the temperature control system, according to the decrease in temperature in the winter days provided the required temperature for the roots. Also, if the pipes are damaged, they can be replaced easily and cheaply. The lifespan of PVC pipes is more than 10 years, while the lifespan of PVC is less than two years. In general, root heating with hot water pipes has more advantages than other methods, including PCMs.

In this article, a Root-Zone Heating system with solar collectors is suggested due to the fact that there are many problems such as the lack of non-renewable energy resources, the production of pollutants, and the high cost of this source. In addition, Equipping the Root-zone system with a flat plate solar collector can also reduce energy consumption, and increases the production of agricultural products.

Materials and methods

The purpose of this study was to design and implement a root-zone system powered by solar energy in a greenhouse at Shahrekord University in December for cultivating roses. The system includes a flat plate collector, heat storage tank, auxiliary heater, and pump. (Figure 1). A circulating pump forces the hot fluid inside the flat plate collector to flow continuously. The hot water pipes are distributed evenly over the planting bed to ensure uniform heat distribution. After heating the plant roots and losing heat, the fluid returns to the collector to be reheated and recirculated. On cloudy or winter days, an auxiliary heater warms the water in the tank to prevent potential temperature drops. To gather additional information, questionnaires were distributed to 20 greenhouse owners in Gilan, Tehran, and Mazandaran. The results showed that, regardless of the seed type, greenhouse owners used 6 mm PE pipes to reduce system construction costs. Additionally, spacing the seeds 30 cm apart increased their crop yield.

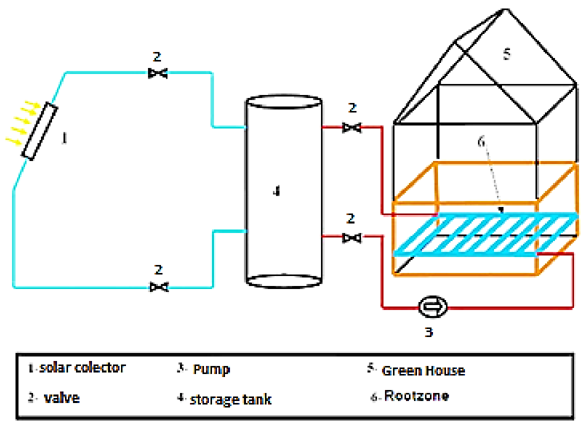

Figure 1. The components of the Root-zone system, the auxiliary system and the heat tank of the Root-zone system

The efficiency of the root-zone system's piping depends on several factors, including the diameter and size of the pipes carrying the fluid, the number of circulation routes, the initial fluid temperature, the spacing of the pipes, and the soil's thermal conductivity, which is influenced by its composition. These factors together determine the overall performance of the piping system. To obtain the heat transfer rate in energy-carrying pipes, there are three types of heat transfer: The displacement heat transfer that takes place in the PE pipe and in the soil and the conductive heat transfer that flows inside the pipe through water and is in the form of equation (1): (Newton's law of cooling)

$$q = hA(T_S - T_\infty) \quad (1)$$

Here h is the displacement heat transfer coefficient in watts per square meter of Kelvin, A is the cross-sectional area in square meters, ‹T_S is the temperature of the fluid and T_∞ is the ambient temperature in degrees Celsius. Conductive heat transfer outside the pipe that will be done by the soil (Fourier's law):

$$q = -kA\frac{dT}{dx} \quad (2)$$

In Equation (2), $\frac{dT}{dx}$ is the temperature gradient in the x direction in degrees Celsius per meter, k is the conductive heat transfer coefficient in watts per square meter Kelvin, and A is the cross-sectional area in square meters. The relationship of one-dimensional temperature distribution without heat generation and permanent conditions in the cylinder and with the determination of the inner and outer surface temperatures of the tube is considered as equation (3):

$$q_r = -kA\frac{dT}{dx} = (2\pi rL)\frac{dT}{dr} = \frac{2\pi lk(T_1 - T_2)}{ln\frac{r_2}{r_1}} \quad (3)$$

In relation (3), r_2 is the outer radius, r_1 is the inner radius, k is the conductive heat transfer coefficient for the pipe material, l is the length of the pipe, T_2 is the temperature of the outside surface of the pipe, and T_1 is the temperature of the inside surface of the pipe. Dynamically, relations (4-7) are used to obtain the thermal power of the greenhouse:

$$s = \frac{2\pi L}{ln\left(\frac{2w}{\pi D} sinh\frac{2\pi z}{w}\right)} \quad (4)$$

In this relation, L is the length of the pipe, w is the distance between the pipes, D is the diameter of the pipe and z is the depth of the pipes:

$$Q_1 = s \times k(T_2 - T_1) \quad (5)$$

Q_1 is the amount of heat required for a branch of piping, k is the thermal conductivity of the soil, T_1 is the temperature of the water inside the pipe and T_2 is the desired temperature of the root. Equation (6) is used to obtain the necessary heat of all the branches:

$$Q = Q_1 \times N \quad (6)$$

Equation (7) is used to obtain the total heat in the greenhouse environment:

$$q = \frac{Q}{A \times B} \quad (7)$$

$65 < q < 130\ w$ is the recommended value for the design of this system. To have the highest efficiency, the length of hot water pipes should not be more than 10 meters, as well as aluminum or copper pipes, because they have a very high cost in installation, for the design of a Root-zone system, from two Pipes with diameters of 6 mm and 9 mm are used.

Heat loss of fluid-carrying pipes

After obtaining the desired root temperature, the heat loss was calculated according to equation (8) in the entire hot water path, from the Root-zone network to the collector.

$$q_{Loss} = U \times A(\bar{T}_{in} - T_{amb}) \quad (8)$$

In relation 8, A is the average side surface of the pipe in square meters, T_{amb} is the temperature of the greenhouse environment, which is usually considered 20 degrees Celsius (Khoshraftar & Ghaemi, 2022), ΔT is the temperature drop along one meter in degrees Celsius, $\bar{T}_{in}$ The average inlet temperature is in degrees Celsius to the pipe. U is the overall coefficient of heat transfer, which is equal to relation (9) (Bergman et al., 2011):

$$U = \frac{1}{R_{tot}} = \frac{1}{h_{out}} + \frac{1}{k_{\text{Cylindrical}}} + \frac{1}{h_{in}} \quad (9)$$

U resistances are obtained according to figure (2).

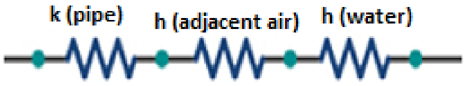

Figure 2. Diagram of internal resistances

In other words, equation 10 is as follows:

$$UA = \frac{1}{\sum R_i} = \frac{1}{\frac{1}{h_i} + \frac{ln^{r_2}/r_1}{2k_{tan\,k}\pi L} + \frac{ln^{r_2}/r_3}{2k_{ins}\pi L} + \frac{1}{h_{out}}} \tag{10}$$

L is equal to the length of the pipe in meters. The heat power lost from the pipe is different for turbulent and laminar flows.

Solar collector

The efficiency of flat plate collectors is calculated from equation (11).

$$\eta = \eta_0 - a_1 \frac{\Delta T}{GT} - a_2 \frac{(\Delta T)^2}{GT} \tag{11}$$

a_2 and a_1 are fixed values for the collector. The values of η_0 are the nominal efficiency of the collector and $T^* = \frac{\Delta T}{GT}$ is the nominal temperature obtained according to the standard table of En-12975 flat plate collectors. $\Delta T = T_{in} - T_a$, where T_a is the ambient temperature and T_{in} is the inlet water to the collector. The thermal power of the collector is in the form of relation 12.

$$Q_c = \eta \times Q \tag{12}$$

The angle of inclination is optimal

Latitude for Shahrekord region is 32.17 degrees and n is number of days per year. In this regard, one n average should be used for each month, which in this research is the n average suggested by Klein (Klein, 1977). The inclination angle δ is the angle between the earth-sun line and the equatorial plane, which changes from 23.45 degrees in summer to -23.45 degrees in winter and can be calculated through equation (13) (Duffie & Beckman., 1991):

$$\delta = 23.45\, sin\left(360 \times \frac{284 + n}{365}\right) \tag{13}$$

ω_s is the sunset angle and is calculated according to the relation (14) (Duffy, third edition):

$$\omega_s = cos^{-1}(-\tan\varphi \tan\delta) \tag{14}$$

Thermal tank

An effectively insulated hot water storage tank can retain the heat for several days, reducing fuel costs. Liquids at the temperature inside the tank are almost homogeneous and uniform, so the thermal resistance of the water in the inner wall of the tank can be ignored. The loss of the upper and lower surface of the tank should be calculated with the Grashof and Rayleigh equations, but because wool and glass insulation strongly prevent heat loss, and the thermal resistance (R) of the insulation is from the thermal resistance of the air around the tank and the wall. The tank is more, and on the other hand, the thermal resistance strongly dominates the thermal heat, so the value of the thermal resistances of the upper surface and the lower surface is reduced, and its value can be ignored. To calculate the heat transfer coefficient from the tank to the environment of the greenhouse, the thermal resistance model of Figure 3 and the relationships required to calculate the heat transfer coefficient were used.

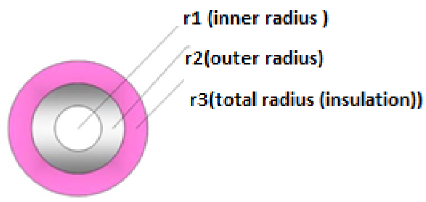

Figure 3. Model for calculating the heat transfer of the thermal tank

The sum of the thermal resistances between the fluid and the environment is calculated from equation 15 :

$$UA = \frac{1}{\sum R_i} = \frac{1}{\frac{1}{h_i} + \frac{ln^{r_2}/r_1}{2k_{tan\,k}\pi L} + \frac{ln^{r_2}/r_3}{2k_{ins}\pi L} + \frac{1}{h_{out}}} \tag{15}$$

L is equal to the height of the tank in meters, k_{ins} is the insulation heat transfer coefficient, $k_{tan\,k}$ is the tank heat transfer coefficient and h_i is the fluid displacement heat transfer coefficient. The proposed heating system tank is double-walled and has a height of 140 cm, an external diameter of 63.69 cm, and a storage capacity of 200 liters. The outer wall of the tank was insulated with 3 cm thick glass wool. The flow of the carrier fluid inside the collector was flowed into the tank by a circulating pump. In this pump, it is possible to adjust the flow rate of the passing fluid. At night, when the temperature inside the greenhouse decreases, the water stored in the tank is heated by an auxiliary source, and then the hot water is transferred to the greenhouse.

Circulating pump

A pump is a device that moves fluids to from one part to another with the help of mechanical action. There are different types of pumps. The circulation pump is one of the types of pumps and it can usually pump liquids up to 100 to 130 degrees Celsius. In this research, due to the high temperature of the water, the pump in question was considered to be a circulating pump that can pump the water flow in a closed path. In closed circuits, the pressure difference, speed difference, and height difference are zero at a point, so the pump head is calculated as Equation 16 (Bergman et al., 2011):

$$H_p = \sum H_L \qquad \sum H_L = h_L + h'_L \tag{16}$$

h_L and h'_L respectively are the head loss of connections and bends and pipe friction based on the Darcy-Weisbach equations. Both parameters are in meters and are obtained from Equation 17 (Bergman et al., 2011):

$$h_L = f\frac{L}{D}.\frac{V^2}{2g} \qquad h'_L = (0.15)h_L \tag{17}$$

The speed of water in urban streams is from 0.2 to 2 meters per second, which was taken into account in the calculations of the speed of 0.3 meters per second. f_T in slow and turbulent flows was obtained as Blasius relation through Equations 18 and 19 (Bergman et al., 2011):

$$f_L = \frac{64}{Re} \tag{18}$$

$$f_T = \frac{0.3165}{Re^{0.25}} \tag{19}$$

The pump power is calculated using Equation (20):

$$P_p = \frac{\rho g Q_p H_p}{\eta_p} \tag{20}$$

where H_p is the pump head, η_p is the pump efficiency, g is the earth's gravity and Q_p is the flow rate in the main pipe.

Results and Discussion

The purpose of designing the Root-zone system with the help of the solar collector is to increase productivity in a certain period of time reduce the consumption of non-renewable energy sources and reduce environmental pollutants. The lowest temperature, about 26℃ (Llorach-Massana et al., 2017), is needed to reach the optimal temperature for the roots. The required heat of the Root-zone system is affected by parameters such as the diameter of the Root-zone bed tubes (d), the number of tubes under the root (N), the distance of the tubes from the root (z), fluid velocity (v) and The area of each section (A) is located . Next, in the first stage, changes in the depth of the pipe placement (Z), and flow rate and its effect on the required heat and temperature are examined. Second, based on the required heat of the system, the number of collectors is checked according to the radiation angle in Shahrekord. In the third stage, the pump type and auxiliary source are examined and the most favorable system is suggested according to the diagrams.

Examining the change in depth of pipe placement (z)

Figure 4 shows the average changes in z (the pipe depth from the root to the soil). According to the figure, T2 increased with the increase of Z, in other words, the value of T2 at z=0.5 is in the range of (60-85) degrees Celsius, and at the value of z=0.2, the value of T2 is in the range of (42-56) degrees Celsius has been placed. Chopra in 2023 stated that when solar water heaters are used in domestic areas, they should be kept at a temperature of less than 100 degrees Celsius; otherwise, the problems of overheating will cause pipe breakage (Chopra et al., 2023).
In addition, due to the high temperature in the heat pipes, the flaking of the condenser is also one of the most important issues that cause the blockage of the heat pipe solar water heater manifold. Figure (3) shows that the most desirable temperature and required heat occur in z=0.4 and z=0.3. Also, Awani et al. in 2017 stated that for the PCM storage system, the most

appropriate depth should be chosen that will produce less heat loss and system performance, so to prevent excessive heat loss and protect the plant, as well as for optimal heat transfer. The user should choose the heat exchanger depth equal to 1 meter in soil. According to the mentioned research, depth is one of the important factors for the thermal system and it should be chosen in such a way that the roots absorb heat easily or are not damaged when exposed to high heat, and the heat source is able to have the desired heat supply.Finally, by examining the modes of 0.2, 0.3, 0.4, and 0.5, the best depth of placement of the pipe from the root is 0.3 meters, which was considered the optimal mode.

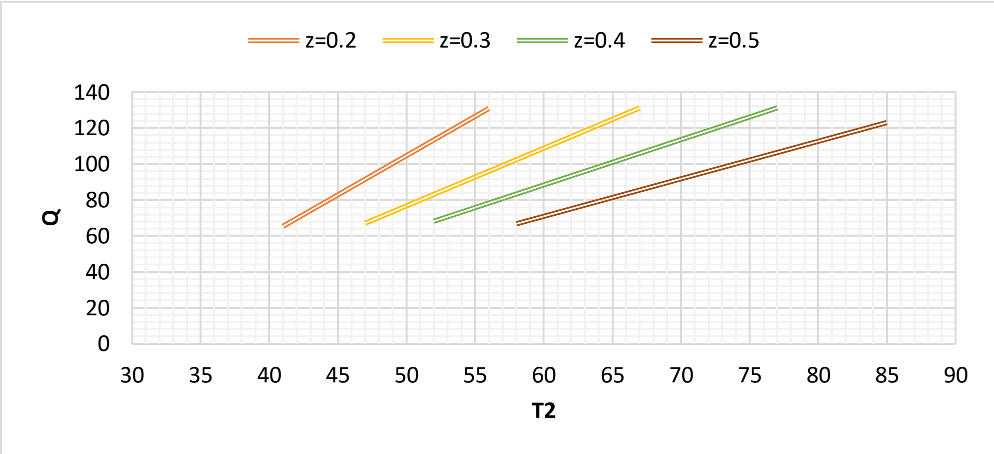

Figure 4. Changes in the depth of pipe placement (z)

Checking the speed change (v)

Stefan Feldar stated in 2017 (Felder & Chanson, 2017) that the interest in numerical modeling in hydraulic engineering and fluid mechanics increased significantly with the development of computer software. Nowadays, a number of complex turbulent flow processes can be calculated by software. Choosing the speed of the heat transfer fluid inside the tubes is another key factor. Figure 5 shows the theoretical increase in the speed of the fluid entering the system from the tank, and the temperature changes at six speeds. In all four z modes, with increasing inlet speed, the required temperature decreases.

The selection of speed should be based on the diameter of the pipe. As Zhen Yu Wang stated in 2015 (Wang et al., 2016), the speed of the pipe should be selected according to the diameter of the pipe, and high speed will cause the loss of pipe resistance, in other words, due to the high speed of the fluid. pipes lose their resistance against holes and breaking. Displacement heat transfer analysis is complicated due to the simultaneous heat conduction and fluid motion process. It should be noted that according to formula 1, the higher the fluid speed, the higher the heat transfer rate (Holman, 1986). According to Figure 5, the speed of 0.1 increases the temperature of the outlet from the tank. The fluid speed in the pipes should be chosen so that the pipe does not lose its resistance against external damage; therefore, a speed of 0.3 m/s is recommended for the heat pump system in the state of z=0.3.

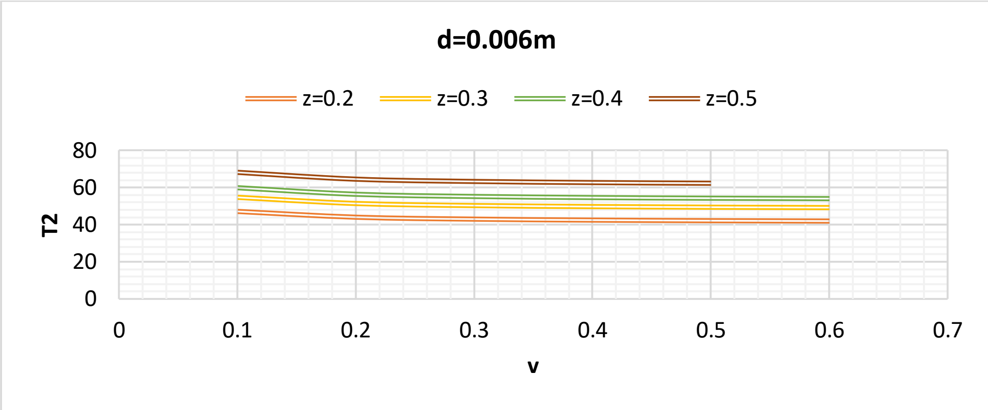

Figure 5. Speed changes in different z modes

Calculation of heat loss in the heat exchanger and tank

According to Figure 6, the main pipe's volumetric flow rate should equal the sum of the hot water flow rates entering the parts. To prevent pressure drop, the diameter of main pipe 1 and main pipe 2 are different, so the diameter of pipe 1 should be greater than the diameter of pipe 2. Q_{loss} was calculated in the main network path.

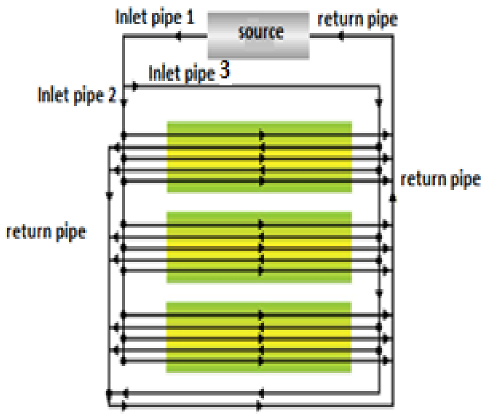

Figure 6. Arrangement of pipes under the root

According to Figure 6, five pipes enter each part, and their paths are different because the pipes lose their heat during the heating path. In order to make the temperature of the entrance to the root uniform, pipe 1 is divided into two pipes 2 and 3 so that pipe 3 flows from the beginning of the part and pipe 3 from the end of the part under the soil. The cooled water at the path's end enters the return pipes 1 and 2 so that the return pipes are in the same direction as the inlet pipes. This type of arrangement is called the reverse return system, which minimizes the pressure drop along the way. The diameter of the pipes was calculated and matched with the INSO14427-2 standard table and the size of the pipes that were close to the numerical calculations were selected. To reduce the calculation error, the flow rate was calculated again in these pipes.

Also, the air temperature around the tank is considered to be 20 degrees Celsius and the tank is made of stainless steel with $k = 55\frac{kW}{m.c^{\circ}}$ .The tank was insulated with wool and glass with a thickness of 3 cm. Equation 12 was used to calculate the heat loss of the tank. Table 1 shows the heat loss in the tank and heat exchanger networks. Based on the results, the heat loss in the tank is 5651.28 watts, considering the thermal resistance of 0.3

Calculation of heat loss in the collector

Insulating the collector pipe is very important to reduce heat loss, as Boadilla et al. insulated the collector pipe with wool and glass in their experiment in 2023 (Bouadila et al., 2023). They also stated that using insulation reduced heat loss from 8.18 to 6.05 W/m2 Kelvin and improved energy efficiency and exergy. To minimize heat loss in the pipe coming out of the collector, this pipe is covered with glass wool insulation with a thickness of 2 cm. It is assumed that the diameter of the outlet from the collector to the tank is 40 mm, with the difference that in order to minimize the calculation error, the temperature of the flowing water in this pipe is 5 degrees higher than the water inside the tank. The results show the total heat in a 100-square-meter greenhouse. According to this table, if the diameter of the pipe of Root-zone network is 6 mm, the required heat is 5658.11 watts.

Investigating the energy produced by the solar heating system

Over the past few decades, solar energy has become a prevalent renewable resource utilized for generating electricity and hot water. One of the most prominent applications of solar energy is the solar water heating system (SWHS), which is an efficient, sustainable, and eco-friendly technique capable of harnessing solar radiation to heat water for domestic hot water usage or space heating. (Zhang et al., 2018). The International Renewable Energy Agency reports a steady rise in the installed capacity of SWHS over the last decade. In 2015, the installed capacity reached 435 GW, surpassing both solar photovoltaics (227 GW) and solar concentrated thermal power (4.8 GW) by a significant margin. In 2015, the solar energy market received an annual investment of $81 billion. Policymakers widely adopt and promote various policies to support the growth of solar and wind energy. These policies include legal and regulatory measures, feed-in policies, subsidy policies, tax reduction policies, and more. These policies are effectively implemented to facilitate the development of renewable energy sources (Adib et al., 2015). Widespread adoption of SWHS technology can significantly reduce fossil fuel consumption and greatly minimize greenhouse gas emissions. With the increasing importance of SWHS application, extensive research was conducted to improve the efficiency of SWHS (Naveen et al., 2023). Zhang et al. in 2018 (Zhang et al., 2018) stated that the choice of collector type plays a more important role compared to other components. In 2023, Bouadila (Bouadila et al., 2023) also stated that hot water production is the largest known use of solar energy. The demand for hot water, whether for individual or collective use (residential, hospitals, space heating, and cooling, traditional bath, etc.), as well as for sanitary purposes, but also for household work and large-scale work, has increased.

In 2018, Zhang provided an overview of the various techno-economic techniques for solar water heating systems. They found that the support policy, natural conditions, type of auxiliary energy, and type of technology strongly influence the payback period of solar water heating systems (Zhang et al., 2018). In 2017, Rezvani announced the necessary standards for the construction and design of the collector with factors such as anti-corrosion materials, resistance to extreme temperatures and pressures, and resistance to water pollution. They also announced that most solar systems are flat plate collectors (Rezvani et al., 2017). This type of collector with glass-coated storage tanks and electrical amplifiers shows a good reliability factor in maintaining the system against lightning and electrical faults and reducing thermal losses. Figure 7 shows the angle of deviation in 12 months of the year. According to this figure, the angle of deviation is less than zero in autumn and winter and reaches its maximum in spring and summer. In other words, the greater the angle of deviation, the more energy received from the sun increases. The deviation angle reaches its maximum in summer.

Figure 8 is the graph of the relationship of time based on the angle of the clock in Shahrekord, and time has a direct relationship with the angle of the clock. As E_T increases, ω increases. Based on this figure, E_T Changes from -67/80 to 68/42, this value is positive in autumn and winter and negative in spring and summer.

Figure 9 shows the thermal power Q_S of the collector based on the azimuth angle θ_z. According to this figure, θ_z has the lowest value in spring and summer and the total thermal power reaches its highest value. Q_S is at its lowest value in autumn and winter. The highest value of Q_S Corresponds to the month of June and the lowest value corresponds to the month of December.

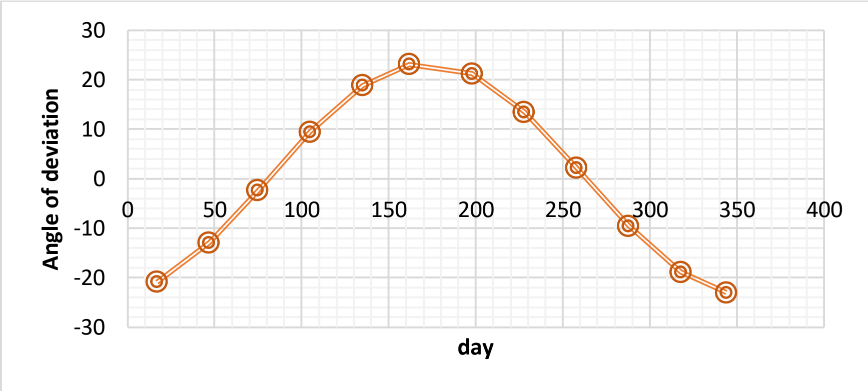

Figure 7. Angle of Deviation in Shahrekord

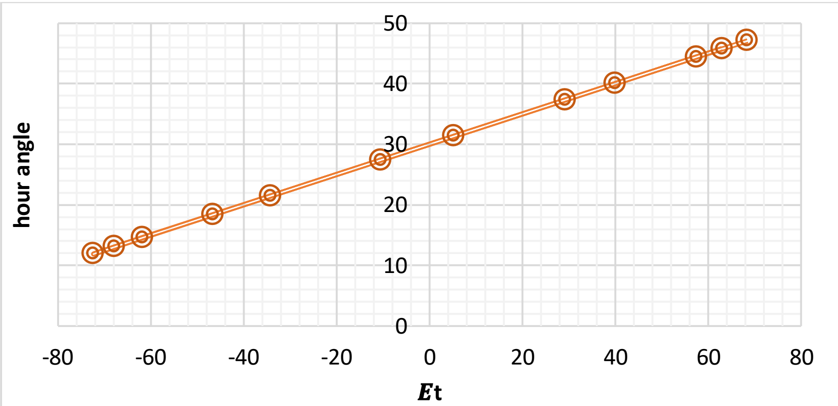

Figure 8. E_T diagram according to the hour angle in Shahrekord

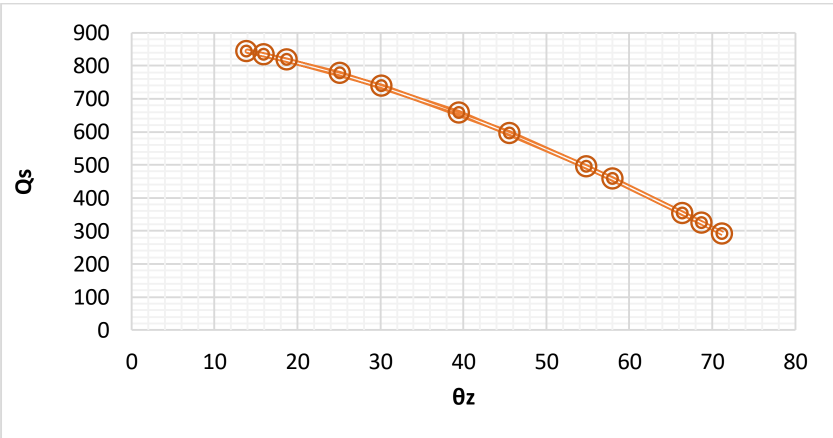

Figure 9. Chart of Q_s in terms of θ_z in Shahrekord

Table 1 shows the thermal power of the solar collector in 12 months of the year at 3 pm. The air temperature was taken from Shahrekord meteorological stations at 3:00 PM. Equations 11 to 12 were numbered in Python software. The amount of radiation intensity in Shahrekord changes based on the optimal angle. The average radiation intensity in Shahrekord is 23.16 $\frac{MJ}{m^2}$. Table 1 shows the final results of inclination angle δ, azimuth angle θ_z, radiant energy Q_s time relationship E_t and hour angle ω in Shahrekord. Formulas 1 to 2 were used to obtain the thermal power of the collector.

Table 1. Changes of δ and ω and Q collector based on the month of the year

month	N	θ_z	ω	E_t	δ	Q_s
January	17	68.79	45.75165	62.98659	-20.916963	323.1
February	47	58.06	39.99889	39.97557	-12.954608	456.9251
March	75	45.65	31.33224	5.30897	-2.4177348	596.1288
April	105	30.2	21.46773	-34.1491	9.4148933	738.5633
may	135	18.73	14.58014	-61.6995	18.791918	817.771
June	162	13.92	11.92282	-72.3287	23.085911	843.5932
July	198	16.01	13.05446	-67.8022	21.183694	832.926
August	228	25.14	18.34647	-46.6341	13.45496	776.4882
September	258	39.51	27.40097	-10.4161	2.2168868	657.2609
October	288	54.91	37.32698	29.28792	-9.5993972	494.0402
November	318	66.45	44.39725	57.56898	-18.911955	353.1421
December	344	71.24	47.11057	68.4223	-23.0496	291.2163

Temperature and the amount of solar radiation are important factors for determining the number of solar panels and heat supply, based on this value, the thermal efficiency and the amount of radiant energy per square meter of the collector were calculated. η was obtained from equation 11 and based on the values of the polar collector model, and its average value was equal to 0.76. Table 2 shows the total radiation energy per square meter of the collector.

Table 2. Total radiant energy in 12 months of the year

Month	$Q_t = Q_c \times Absorbent\ surface\ (w)$	$Q_c = \eta \times Q_s(w)$	Returns(η)
January	387.76	246.9868	0.764428
February	548.73	349.5112	0.76492
March	717.24	456.8426	0.766349
April	890.19	567.0007	0.767708
May	987.84	629.2017	0.769411
June	1021.62	650.7178	0.771364
July	1010.56	643.6749	0.772788
August	940.80	599.2407	0.771732
September	794.37	505.9706	0.769817
October	595.80	379.4945	0.768145
November	424.62	270.4646	0.76588
December	349.27	222.4685	0.763929

Figure 10 shows the change of heat produced by the collector in 12 months of the year in Shahrekord.

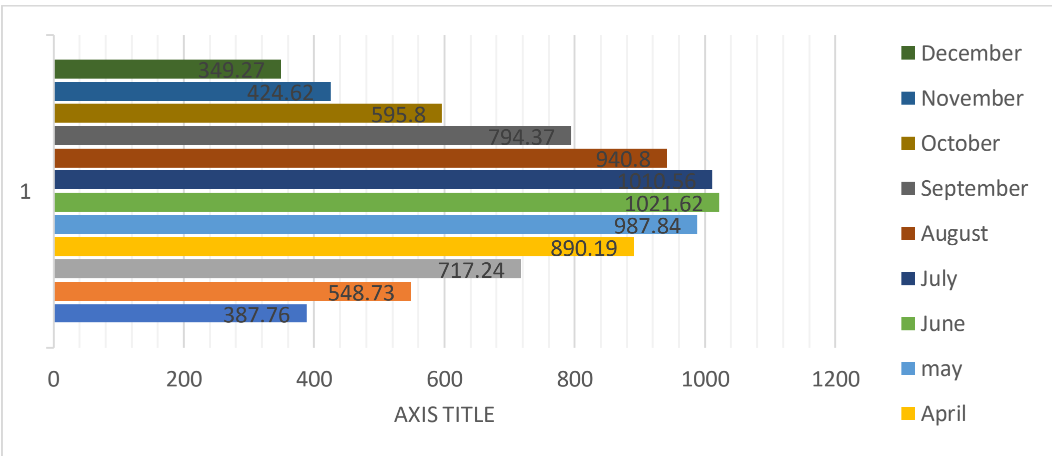

Figure 10. Heat produced in 12 months of the year in Shahrekord

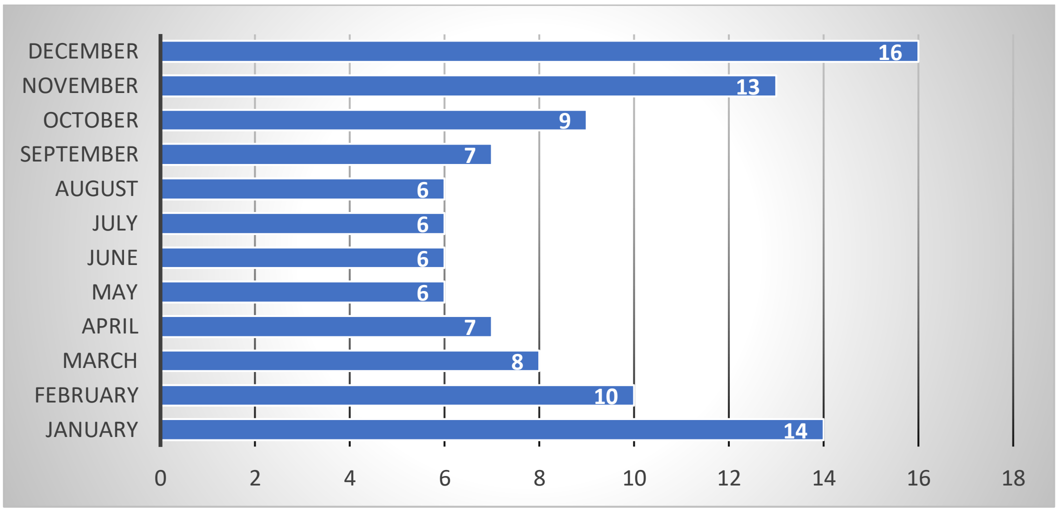

Figure 11. The number of collectors needed in a 100-square-meter greenhouse in Shahrekord

5658.11 w is needed to provide the necessary heat for a 100-meter greenhouse. According to Table 4, 16 collectors with dimensions of $94 \times 200cm^2$ are needed to supply this heat in December, with the lowest amount of sunlight. Figure 11 shows the number of collectors needed in 12 months in Shahrekord. By combining the heat system, i.e. solar collector and auxiliary source, the number of installed solar panels can be reduced.

Apart from solar radiation, several other factors can impact the efficiency of a collector, such as the average temperature and rainfall over time. Additionally, other weather elements, such as the type and timing of precipitation, and the amount of sunlight, can also play a significant role in determining the effectiveness of a collector. The influence of average wind speed and direction, number of days above zero point, extreme weather, and local geography (Zhang et al., 2018). In order to absorb the most solar radiation, the collectors are installed in an inclined manner. The position and angle of the collector installation relative to the horizon affect the performance of flat plate solar collectors. It is possible to maximize the amount of received radiation by adjusting the angle of the collector relative to the horizon on a monthly basis. The optimal monthly angle in Shahrekord varies from zero degrees in May to 22 degrees in December, but due to the impracticality of changing the angle of the collector on a monthly basis, by changing the angle of the collector on a monthly basis, you can benefit from the maximum sunlight. In 2017, Bracamonte stated that they investigated the thermodynamic performance of a glass vacuum solar collector at different collector tilt angles (10, 20, 27, and 45) and with four transient inputs from top to bottom, and finally, it was determined that A low tilt angle reduces the stored energy (Bracamonte, 2017).

Auxiliary Source

In 2023, Boadilla et al. stated that domestic solar water heating applications have been established worldwide, especially in sunny countries. Its main disadvantages are solar energy's intermittent nature and utility during non-sunny hours (Bouadila et al., 2023). Therefore, several thermal storage strategies for solar energy should be explored. In 2018, Zhang stated that solar collectors cannot always meet user demand during the day or in winter. Therefore, solar energy cannot be completely replaced, so the need for additional fuel is greater in months when the solar intensity is low, and the ambient temperature is lower (Zhang et al., 2018). Liquefied petroleum gas (LPG) is the most efficient and has a high calorific value, hence considered as the best fuel in the study (Nahar, 2003). But agricultural access to energy sources is very important. Some greenhouses are built far from the city, and sometimes they do not have access to gas energy, but most of them have access to electricity, so the considered auxiliary source works with electricity. According to section 4 and based on the calculations, the maximum thermal power required on a cold winter day with a minimum temperature of 8 degrees Celsius is about 5658.11 watts. Therefore, taking into account the efficiency of the electric heater, it is suggested to use a two-phase flanged rod element of 3 kW, which provides the thermal power of the entire solar system of about 6000 watts for night time. Rod elements can be made and designed according to the required power. The heater is installed inside the tank, and for the temperature control system, a separate thermostat is used, which is installed inside the tank water.

Pump

SWHS usually uses an electric pump to circulate water between a storage tank (ST) and a solar collector. Awani in 2017 evaluated the thermal performance of a heat pump with a flat plate solar collector. Their results showed that the maximum COP of the heat pump was 5.5 at 13:00. Also, they used a pump to circulate hot water for PCMs in their experiment. Based on these results, in order to circulate water in a greenhouse of 100 square meters, a circulating pump with a pump head of 1.93 meters with a power of 781 watts is needed, and according to the catalog of different companies, an 800-watt pump model XKP 804E from Liu company was selected.

System implementation

In this research, the effective parameters in the design of Root-zone system were investigated to plant roses in 10 meters of two-sided greenhouse space of 500 square meters in shahrekord in December (figure12). The speed of water in energy-carrying pipes is 0.3 m/s in order to have a positive effect on the heat transfer rate. The distance between the pipes was 20 cm. In general, the heat source system was designed to need the least heat and temperature from the heat source side. To provide energy at night or on cloudy days, from electric thermal elements we use the tank to heat the water. Heat supply was calculated based on the coldest month of the year (December). By turning on the single heating element in the tank, the number of collectors can decrease.

The results showed that:

- As the depth of the soil increases, the desired temperature should increase to 26 degrees to achieve the result. The experimental results were less than 7% different from the theoretical results.
- The collector could easily raise the root temperature to 26 degrees, Which means collectors can heat larger greenhouses without any problems.
- Increasing the thickness of pipe insulation did not have a great effect on the outlet temperature of the collector. More precisely, the percentage difference between theoretical and experimental data was less than 5%.
- By increasing the speed from 0.3 to 0.4, the required heat for soils with more depths increased, which results indicate the accuracy of theoretical data estimation. The error percentage was less than 9%.

Table 3 shows the error rate of theoretical and experimental calculations at different depths. This method has less error than the PCM method because the water can be installed at a lower temperature at a lower depth to keep the root at the desired temperature. The cost of piping and implementing this method is much lower than PCM methods. The implementation of this method for an area of 10 square meters cost about 200 dollars, while the installation of PCMs for 10 square meters was estimated at about 270 dollars, which, unfortunately, was not easily found in the market for accurate experimental calculations.

Table 3. Comparison of experimental and theoretical values

Soil depth (m)	Estimated amount	Heat required in the experiment	Percentage Error
0.20	43	44.6	3.59%
0.30	49	51.8	5.41%
0.40	55	58.5	5.98%
0.50	61	65.3	6.87%

Conclusion

In this study, we modeled a root-zone system incorporating a solar collector, a 200-liter tank, an auxiliary heater, and a pump for heating a 100 m² greenhouse. The system was tested for its suitability in cultivating roses in a 10 m² area. The results included theoretical analysis and correlation of thermal phenomena in Shahrekord weather conditions. Also, the required heat in a greenhouse with specific dimensions was calculated, and the effective parameters such as water speed (v) and the depth of placement of the tube from the root (z) were checked. Finally, graphs and tables were presented. Based on the cases mentioned in the previous section, the results of the analysis are as follows:

- ✓ The choice of fluid speed, the distance between the pipes, and the depth of the pipes can affect the heat efficiency.
- ✓ By reducing the speed of the water entering the heat pump system, the required temperature for this system increases, and as a result, the required heat of the system increases.
- ✓ This system needs an auxiliary source to prevent pressure drop during cold nights and days.
- ✓ The best position of the pipe is 0.4 and 0.3 meters from the root. Greenhouse keepers often place the crops at a distance of 30 cm from the greenhouse floor.
- ✓ Most of the greenhouse owners were dissatisfied with the high consumption of energy and the production of pollutants by the Root-zone system. However, the cost of energy consumption and the production of pollutants can be minimized by installing solar collectors.
- ✓ This system was implemented with the help of a solar collector.

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