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Modelling of soil temperature by using Phase Change Material (PCM) to regulate the plant growing media temperature

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Abstract

The temperature control of the agricultural greenhouse is important issue and to sudden temperature, changes during the growing plants are one of the problems that need to be controlled. Temperature control can be achieved in greenhouses established with the novel technological systems, but these systems are expensive systems that requires technical knowledge and infrastructure. In this study, a seasonal thermal energy storage using Phase Change Material **(**PCM) composite material investigated to regulate day time soil temperature in the greenhouse. The overall purpose of the research was to identify the mechanisms of heat transfer in soil covered by phase change materials. The PCM was encapsulated in to expanded perlite and soil temperature with and without using the PCM were compared. By using the experimental data, a mathematical model that can simulate the temperature of the soil in the greenhouse was developed According to the results, the research included experimental works as well as theoretical analysis.

Keywords: Soil temperature, phase change material (PCM), greenhouse applications, modelling of soil temperature.

Introduction

In agricultural applications, especially in greenhouses the needed energy amount is high. The increasing costs of energy production and the limited resources make it necessary to develop new methods for the efficient use of energy. In an effective agricultural activity, energy uses must be in controlled and in the logical range. The food supplies in the world are directly depend on the energy (Ziapour and Hashtroudi, 2017). Already, developing in energy use in the agriculture is a response to population increasing, limited supply of useful lands and demand for better standards of living (Banaeian et al., 2011).

Temperature change during the crop production is the main problem for in terms of plant growth and yield. The advent of the greenhouse is intended to control the environment to improve the quality, stabilize the yield and prolong the production season. A well-designed greenhouse should maintain an optimum environment for healthy plant growth and maximum yield (Tuntiwaranuruk et al., 2006).

Because of the high-energy consumption and global warning in recent years, energy conservation and storage applications have become extremely important. Energy storage seems as a good opportunity to solve the energy problems as well as to improve new renewable and clean energy sources. To meet energy needs of the developed communities, the renewable energies can be used conjunction with energy storage systems. In addition, efficient and compact energy storage systems seem to be important parameters to improve the use of renewable sources (Kenisarin and Kenisarina, 2012; Gürmen, 2019).

Thermal energy storage can be stored as a change in internal energy of a material as sensible heat, latent heat and thermo-chemical or combination of these. The latent heat storage method, in which energy is stored in the form of latent heat in phase change materials (PCM), plays an important role in different application areas. This technique is particularly attractive with respect to other techniques due to two main advantages:

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i) Phase change process is nearly an isothermal process.

ii) It has larger heat storage density with smaller temperature swing.

Phase change materials (PCM) are one of the most used materials in thermal energy storage and temperature control of many engineering applications (Zalba et al., 2003; Sharma et al., 2009; Zhou et al., 2009; Rathod and Banerjee, 2013). PCMs store energy by absorbing and releasing of heat in phase change processing in the form of the latent heat of fusion. Depending on their phase change states, PCM are classified in four categories liquid-gas, solid-liquid, solid-gas and solid-solid PCM (Prakash et al., 1985; Jamekhorshid et al., 2014; Gürmen, 2017).

The PCM could absorb sun energy inside greenhouses during the day, and release the heat in the night to provide a thermal comfortable environment for crops. This feature of PCM could noticeably reduce the temperature difference between day and night in greenhouses, which could effectively increase the crops yield (Mu et al., 2022). For this application, a PCM having suitable melting / freezing temperatures and heat of fusion should be selected.

In this study, PCM composite material was used in order to keep the soil temperature constant in the greenhouse. The PCM material used was prepared using the method of trapping PEG in expanded perlite pores. Owing to this encapsulation process, the solid-liquid phase change process takes place within the pores and leakage was prevented. The melting and freezing temperatures were determined for prepared composite, as 21°C and 6 °C, respectively and the phase change enthalpy was calculated as 130 J/g. Perlite has been preferred in the preparation of composite PCM due to its porous structure and being a natural rock widely used in agriculture. This study concerned to improve of mathematical and numerical models different modes of heat transfer interaction with the environment in the soil by the layer containing PCM. The experimental data obtained during measurements of the soil thermal properties conformed to the theoretical model.

Material and Methods

The main aim of this research was to identify the mechanisms of heat transfer in soil covered by PCM enclosed perlite to regulate the soil temperature. The research included experimental works as well as theoretical analysis.

The used PCM composite including PEG and EP was prepared using a vacuum impregnation method. Initially 25:75 mass ratio of PEG and EP were weighted with 0.001 g accuracy. Weighed EP was placed in the vacuum set and the prepared mixture was added it slowly under vacuum at 30°C. Then, the obtained mixture was placed into an oven at 60°C for 12 hours. The prepared form stable PCMs were included 25 % PEG wax by weight. The phase transition temperature and latent heat of prepared PCM composite material was determined by DSC analysis (Perkin Elmer Diamond TG/DTA) at a heating/cooling rate of 5◦C/min from −45◦C to 5◦C by using purified nitrogen at a flow rate of 10 ml/min.

In order to verifying the mathematical model, only a part of the soil is covered with the prepared PCM and other part was left uncoated in the same greenhouse, placed in Menderes, Izmir, Turkey. The soil was covered with of 10 mm-thick of PCM composite over the growing media. Temperatures at different levels of the soil were hourly measured by using thermometer. The experiments were performed from in March 2021.

The soil temperature was measured by using ST4-05 Soil Temperature Probe and the probes were placed into the soil at 10, 20 and 30 cm depth. Soil temperatures were measured every 60 minutes for 24 hours.

Mathematical Model

In the theoretical part of the research, a mathematical model of heat transfers in PCM covered soil developed. In the model, it was subjected to environmental impacts by radiation and convection. This includes the formulation of the set of equations that combine temperature profile in the soil with heat fluxes at its surface as well as the values of thermophysical properties of the soil that influences the process of heat transport.

The soil temperature with and without PCM composite inside an agricultural greenhouse having soil inside growing media is considered T_s (°C). When PCM composite covered soil in the greenhouse growing medium and the soil is heated by solar radiation, its energy is lost to the cover by convection, conduction and radiation.

To simplify the analysis, the following assumptions for the heat transfer processes in the soil were used for model development:

1. One dimensional heat transfer occurs; the temperature gradients exists along the height only
2. The heating system is quasi-state condition
3. The air and the soil temperatures in the greenhouse are homogeneous and isotopic.
4. Thermal properties are independent to temperature.

The layers in the growing media is shown in Figure 1.

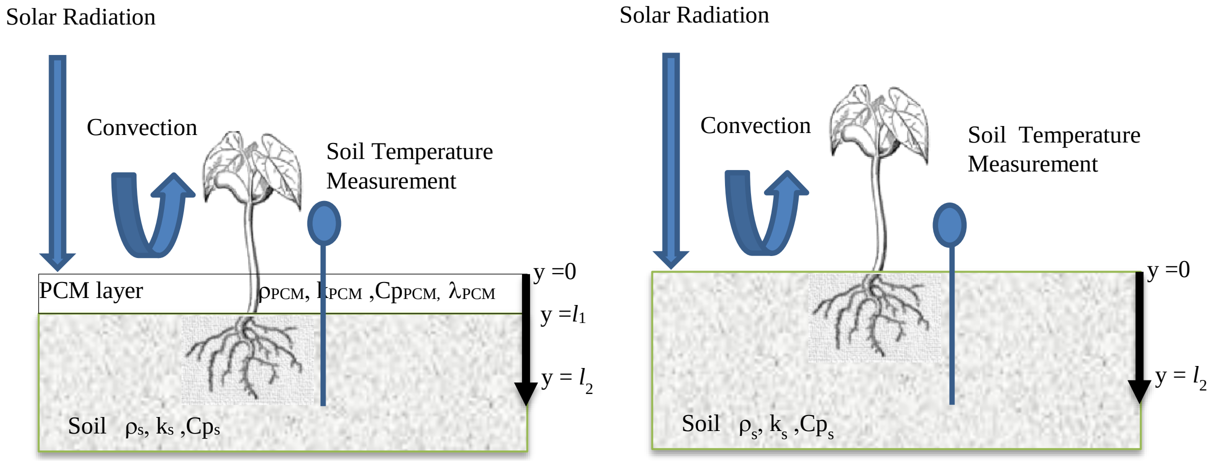

Figure 1. The layers in the growing media with and without PCM.

The one dimensional temperature distribution $T(y,t)$ in the soil is described by conductive heat transfer equation:

$$\rho C_p \left(\frac{\delta T(y,t)}{\delta t}\right) = \frac{\delta}{\delta y}\left(k_s \frac{\delta T(y,t)}{\delta y}\right)$$

where ρ density (kg/m^3), C_p specific heat (kJ/(kg K)), t time (s), k_s thermal conductivity of soil (W/(m K)).

Subjected to the boundary condition:

$$k_s \frac{\partial(T,y)}{\partial y} = h\big(T_i(t) - T(y,t)\big) + q_r(t)$$

At y=0 at surface

Convective heat transfer to the air is due to the natural convection. In the model simplified the calculation of the convective heat transfer coefficient McAdams correlation was chosen and h can be calculated by the following equation (Bergman et al., 2011).

$$h = 0.1\left(\frac{g\beta\Delta T}{\nu^2}Pr\right)^{1/3}\frac{1}{k_a}$$

where h convective heat transfer coefficient(W/(m^{2}K)), g gravity acceleration (9.8 m/s^2), ν kinematic viscosity (m^2/s) , β thermal expansion coefficient (1/K), Pr Prandtl Number, k_a thermal conductivity of air (W/(m K)).

When the air temperature is in the range between 0-45 °C, the above equation can be simplified to the form in which heat transfer coefficient is only a function of temperature difference (Jaworski, 2019):

$$h = 1.15\Delta T^{1/3}$$

$q_r(t)$ is solar radiation (W/m^2) transmitted through the greenhouse cover to the upper surface of soil.

$$q_r(t) = \varepsilon\sigma\left({T_s}^4 - {T_a}^4\right)$$

where ε emissivity, σ Stefan-Boltzmann constant (5.67 10^{-8}W/m^{2}K^4).

The transient heat transfer equation of PCM layer

$$\rho_{PCM}\frac{\delta H}{dt} = k_{PCM}\frac{\delta^2 T(y,t)}{\delta h^2}$$

where ρ_{PCM} density of PCM (kg/m^3), H enthalpy of PCM (kJ/kg), k_{PCM} thermal conductivity of PCM (W/(m K)).

Enthalpy of PCM

$$H = \int_{T_0}^{T_m} {C_p}_{PCM} dT + \lambda_{PCM} + \int_{T_m}^{T_2} {C_p}_{PCM} dT$$

where ${C_p}_{PCM}$ specific heat (kJ/(kg K)) and λ_{PCM} heat of fusion of PCM (kJ/kg).

Boundary condition:

$$\text{at } y=l_1 \qquad k_s\frac{\partial(T,y)}{\partial y}=0$$

l is solid height from surface (m)

Initial condition: $T(y,t)_{t=0}=T_i$

Heat transfer equation for inside air of the greenhouse is formulated as:

$$C_{pa}\rho_a V_R\frac{\partial T_a(t)}{\partial t}=\sum Q_s-Q_{leak}$$

where Q heat transfer rate (W) and C_{pa} specific heat of air (kJ/(kg K)).

Table 1. Thermal physical properties of the soil and PCM

	ρ (kg/m^3)	Cp (kJ/kg K)	λ (kj/kg)	k (W/m K)	T_m (°C)
Soil	1110	1.13	-	0.097	-
PCM	1120	2.49	130	0.212	21

The proposed model of heat transfer in the soil describes their temperature changes described under thermal transfer processes by the boundary conditions. Selected problems, similar to those realized in an experimental study were solved numerically, using one dimensional control volume approach with Euler's method for integration in time.

Results and Discussion

Thermal properties of the used PCM is an important factor influencing the ability of energy storage of the PCM layer over the soil. The important point of applying PCM on the soil surface is to select PCM with suitable melting temperature. For selected climate condition and soil, when the melting temperature of PCM is high, the quantity of heat stored by PCM will be low. When the melting temperature is low, to obtain a comfortable soil temperature for plant will be hard, at night time. For this reason, the phase change temperature of the PCM to be used should be suitable for the selected climate region. For this reason, initially the thermal properties of the prepared PCM composite were determined by using DSC analysis and obtained data are given in Figure 2.The melting and freezing temperatures and latent heat values of the prepared composite PCM are 20.64 °C, 6.24 °C and 130.7 J/g, respectively.

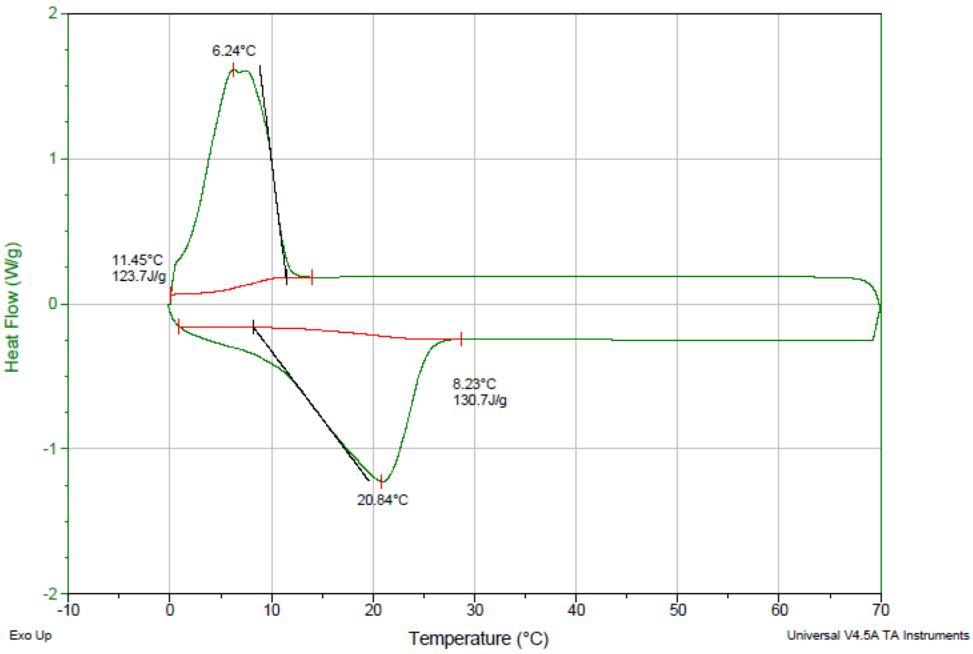

Figure 2. DSC curves for prepared composite PCM

The model's accuracy and applicability were tested and compared experimental results at surface, 10, 20 cm and 30 cm level from the surface which is suitable for plant growth. The experimental and model results were in agreement as shown in Figures 3, 4, 5 and 6.

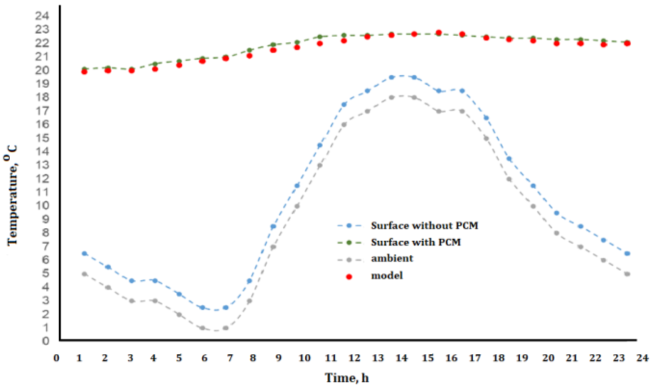

Figure 3. Comparison of temperatures between experimental and model results at soil surface

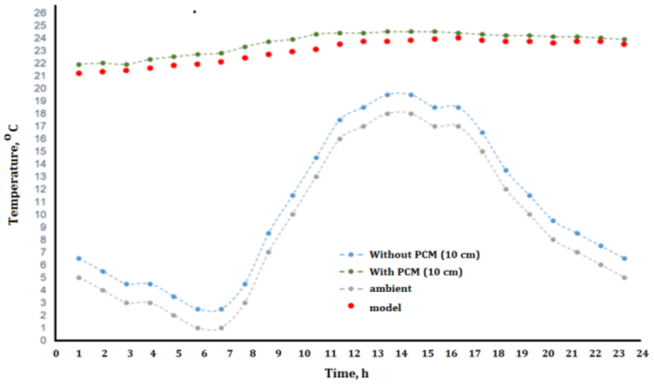

Figure 4. Comparison of temperatures between experimental and model results at 10 cm from the surface

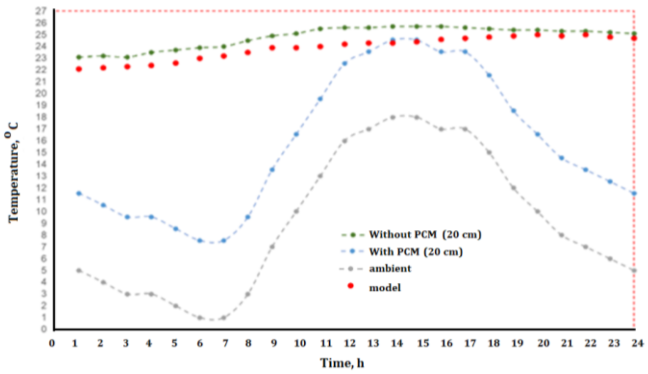

Figure 5. Comparison of temperatures between experimental and model results at 20 cm from the surface

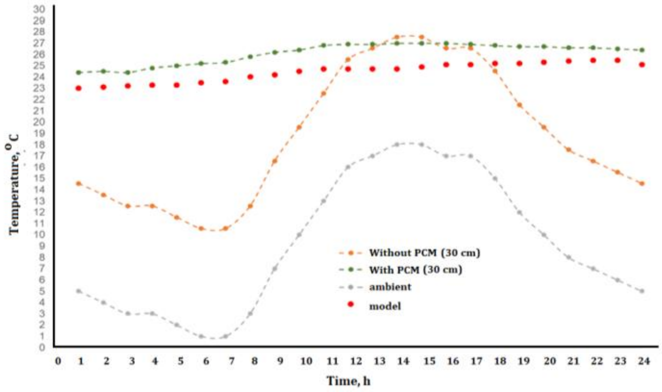

Figure 6. Comparison of temperatures between experimental and model results at 30 cm from the surface

The experimental results show that, soil temperature becomes nearly constant when the soil was covered with PCM layer as expected. Using the PCM layer, the obtained soil temperature ranges was from 21 to 27 °C and this range is appropriate for the plant growth. The maximum temperature value difference between the PCM covered and not covered soil at surface, 10, 20 and 30 cm from the surface was found as 18.5, 17.45, and 16.35 and 14.75 °C, respectively. Tuntiwaranuruk et al. (2006) studied with rice husks which was covered the soil to reduce soil temperature and they reported that the reduction due to rice husks covering soil in maximum values of soil temperature at 10 and 20 cm from the surface was found as 5.00 and 2.83 °C, respectively. This study rice husks used to decrease solar radiation effect. In order for plants to grow healthy, it is important that their roots be not affected by temperature changes throughout the day. It has been determined that soil temperatures can be stabilized thanks to the soil covered by PCM. The average value of the soil temperatures were measured as 21.82, 23.62, 23.82 and 26.11°C at surface, 10, 20 and 30 cm depth from surface, respectively. It is obvious that soil temperature without PCM is lower than that with PCM. According to the results, it can be seen that PCM also helps to improve the heat transfer between the soil surface and air in the greenhouse.

The soil temperatures calculated from the mathematical model were found to be in well agreement with the measured temperatures for each level of the soil. The average value of soil temperature differences between the measured temperatures and the temperatures calculated from the proposed model were 0.2, 0.67, 0.91 and 1.46 °C at surface, 10, 20 and 30 cm depth from surface, respectively. Wang et al. (2020) reported that, the simulation results are higher than the observed values at depths of 0.2m and 0.3m. In order to determine the suitability of the proposed model, standard deviations were calculated and standard deviations between mathematical model and measurement temperatures were found as 0.16, 0.21, 0.35 and 0.36 for surface, 10 cm, 20 cm and 30 cm depth, respectively. Mashonjowa et al. (2013) reported values of the mean standard errors between the calculated and measured air and crop temperatures of 1.8 °C and 1.9 °C, respectively. In the present study, the proposed model gave more approximate results for soil temperature.

Although the model compatibility is high in the studied soil depths, it is seen that the standard deviation increases slightly as the soil depth increases. This deviation is thought to be due to the increase in the difference between air temperature and soil temperature as the depth increases.

Conclusion

In the present paper, a mathematical model of analysing the thermal performance PCM over the soil is developed. It is concluded that the proposed mathematical model can be used to predict soil temperature with and without PCM over the soil in an agricultural greenhouse. According to the experimental results, it is seen that by covering the soil in the greenhouse with PCM, a suitable environment for plant growth will be provided by preventing sudden changes in soil temperature during the periods when day and night temperature differences are high. Thus, the costs of heating systems used in greenhouses can be reduced.

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