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RESEARCH ARTICLE

SOIL TEMPERATURE CONTROL FOR GROWING OF HIGH-VALUE TEMPERATE CROPS ON TROPICAL LOWLAND

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ABSTRACT

Low soil temperature (14°C–20°C) favours growing of high-value temperate crops that are known to have higher return per hectare of land than other widely cultivated crops, thereby presenting increased income to farmer. However, due to high soil cooling load, growing these crops on tropical lowland area is a challenge except through greenhouse farming or on few cool higher altitudes with resemblance of temperate climate. Greenhouse farming involves cooling the entire volume of planting zone and is energy intensive, while few cool highlands are not sufficient to achieve food security in this direction. This study aims at application of chilled water for direct cooling of soil, to create favorable soil conditions for optimal performance of planted temperate crops. However, soil cooling using vapour compression refrigeration system may not be economically viable. Solar thermal chilled water production system is presented in this study to supply the cooling. The system consists of absorption refrigeration system and dimensioned size of soil bed with chilled water pipe network. The study includes modeling of soil cooling load to determine the refrigeration power required to overcome such load. The modeled system matched well with the experiment; having standard deviation of 1.75 and percentage error of 12.24%. Parametric analysis of the soil cooling showed that temperatures of cooled soil were significantly affected by chilled water flow rates. The regression equation developed from the Analysis of Variance (ANOVA) is suitable for predicting cooled soil temperature. The cooling process is technically feasible, with potential for greenhouse gas emission reduction.

KEYWORDS

Soil Temperature, Greenhouse, Farming, Temperate Climate, Vapour Compression Refrigeration System, Solar Thermal

1. INTRODUCTION

Most of the physiological processes of planted crops are controlled by soil temperature which if higher than optimal, will alter the root growth and functionalities of the crops; a phenomenon that is very common with the hot tropical climate soil (Kim and Joo, 2020; Mongkon et al., 2014). However, Temperature crops, mostly as high-value, crops such as cabbage, lettuce, broccoli and carrots are generally referred to as cold season crops with their adaptability to low temperature; usually between 18°C and 20°C (Sabri et al., 2018). Hence difficulty in their cultivation on hot tropical lowland areas except on some few highland such as Jos Plateau in Nigeria and Cameroon highland in Malaysia. The effects of climate change have equally led to decline in temperate crops farming in these areas. Alternatively, greenhouse farming system is commonly used in the tropics to cool down the air volume of planting zones of some high-value crops against excessive heat (Campiotti et al., 2016). However, soil temperature has been found to have more effects on the development of planted crops than air temperature (Labeke et al., 1993; Ogbodo et al., 2010). Furthermore, radiant floor cooling has been reported in the literature as a more energy efficient system than air-cooling system due to the better thermal capacity and less pumping energy requirement of water than air (Seo et al., 2014). Like the greenhouse cooling, soil temperature control requires energy expenditure which if alternatively provided, will not only make the system economically viable but also environmentally benign (Wongkee et al., 2014; Zarella et al., 2014; Zhou et al., 2014; Zhou et al., 2019). A prominent alternative cooling system is absorption chillers that utilize low-grade energy such as solar for chilled water production. Chilled water production through application of solar thermal technology is one of the interesting research areas in the tropics where there is high solar potential that is available in phase with the cooling load.

Presented in this paper is a system comprising of a solar thermal chilled water via absorption refrigeration to offset the cooling load of a dimensioned soil bed. Absorption cooling system is a typical thermally activated technology that is found suitable for utilization of low-grade thermal energy such as solar energy via solar collector. The soil cooling process involves channeling chilled water through chilled water pipe laid under the surface of the soil for heat removal. The objectives of the paper include; to develop mathematical model for soil load and equivalent refrigeration plant, to develop model equation for chilled water flow rates suitable for a range of soil temperatures and to validate the model with experimental results, to perform sensitivity analysis of the soil cooling to chilled water flow rates and temperature, and ambient air temperature. The significance of the study can be found in the areas of better utilization of free energy source (solar energy), not only for agricultural soil cooling applications but also for comfort cooling in building. Successful

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application of this study equally aims to aid domestication of high-value temperate crops in the tropical regions which could help to contribute to national economy via reduction in importation of the temperate crops.

2. Mathematical Models Development

Soil temperature is direct consequence of the solar radiation heat on the earth surface. mathematical models are developed to estimate the amount of the heat gained by the affected area of soil (Niu et al., 2015; Wu et al., 2015). This helps to determine the equivalence amount of the cooling capacity required to offset the heat to appropriately control the soil temperature. The heat removal is achieved through the heat exchange between the surrounding soil and the buried chilled water pipe.

2.1 Soil – chilled water pipe heat transfer model

As presented in Fig. 1, conductive heat transfer from the top soil to the chilled water is due to the temperature difference between the two sections. However, in the absence of a heating source, an homogenous temperature is possible between the two sections; when the temperature difference decay brings the conductive heat transfer close to zero (Feng et al., 2016). The summary of the soil and chilled water pipe heat transfer model is as itemized below;

- Heat transfer resulting from the temperature difference between the soil surface and the ambient environment under the influence of solar radiation ($\bar{Q}_s$)
- Vertical heat conduction from the soil surface down to buried chilled water pipe (Q)
- Heat gained by the chilled water through the pipe via convection and conduction (U_t).

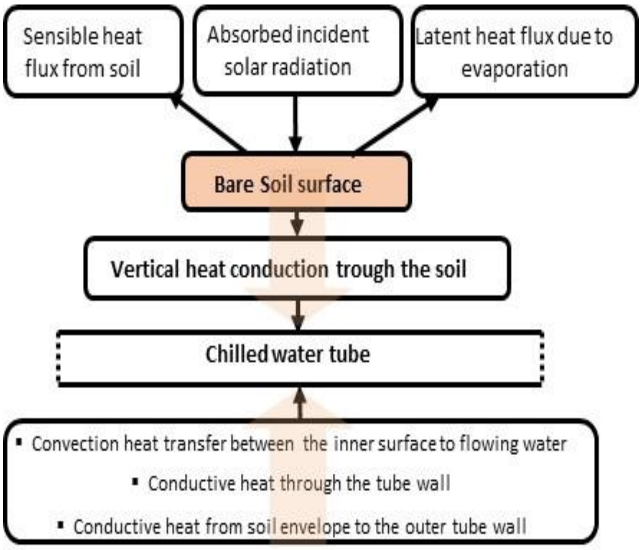


Figure 1: Heat transfer model

The net heat energy balance between the soil surface and the ambient atmosphere is expressed as;

$\bar{Q}_s = R_n - (\bar{Q}_h + \bar{Q}_L)$ (Ricardo et al., 2008).

With respect to Stefan-Boltzmann law, the net radiation absorbed by soil (R_n) is expressed as;

$R_n = (1-\propto)Q_{inc} + \sigma \mathcal{E}_s(\mathcal{E}_a T_a^4 - T_s^4)$ (Tsoutsos et al., 2009; Novak, 2010)

The heat transfer between the chilled water and the surrounding soil is determined using the '*total heat transfer coefficient'* (UA) across the wall of the chilled water pipe from the surrounding soil (Fig. 2).

$$Q = UA(T_p - T_w)$$

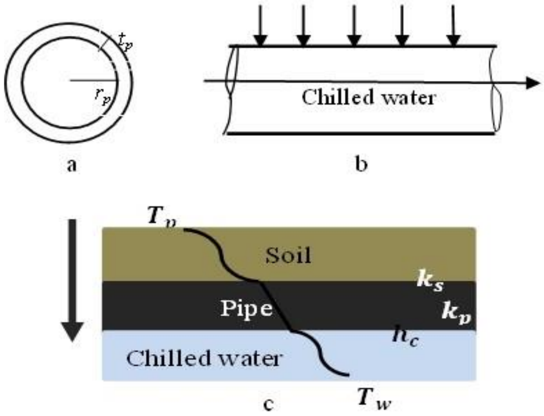


Figure 2: (a – c) Chilled water tube cross section and flow of heat across the sections

The overall heat transfer coefficient (UA) is expressed in terms of the resistance to heat transfer across the chilled water pipe (Lee and Strand, 2008). The resistance against the flow of heat across the chilled water pipe, from the surrounding soil is represented in Fig. 3. Perfect contact is assumed between the soil and the chilled water pipe, thus temperature of the soil in contact with the pipe and that of the pipe are equal (Niu et al., 2015).

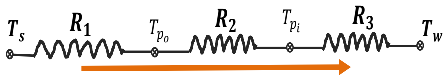


Figure 3: Heat transfer resistance across chilled water pipe

Resistance to convective heat transfer between the inner surface of the pipe and the chilled water (R_1) is expressed as;

$$R_1 = \frac{1}{hA} = \frac{1}{2\pi r_t l h_c}$$

Where; $h_c = \frac{N_u k_w}{2r_t}$ (Subramaniam, 2008)

Resistance to conduction heat transfer from the outer surface of the pipe to its inner surface (R_2) is given as;

$$R_2 = \frac{1}{2\pi l k_p} \ln\left(\frac{r_t + t_p}{r_t}\right)$$

Resistance to conduction heat transfer between the surrounding soil and the external wall of pipe (R_3) is expressed as;

$$R_3 = \frac{1}{2\pi l k_s} \ln\left(\frac{r_t + t_p + d_s}{r_t + t_p}\right)$$

Total resistance; $R_t = R_1 + R_2 + R_3$

Total heat transfer coefficient;

$$U_t = UA = \frac{1}{R_t}$$

Total heat transfer is expressed as;

$$U_t[T_{cw\_out} - T_{cw\_in}]$$

Thus, the heat transfer occurring between the surrounding soil and the chilled water in the pipe is equivalent to the amount of heat gained by the chilled water as it flows through the earth pipe. The chilled water outlet temperature (T_{cw_out}) is majorly influenced by the amount of heat transferred from the soil (cooling load), through the pipe to the chilled water.

2.2 Soil cooling load

Cooling load calculation plays an important role in the estimation of heat from heating, ventilation and air-conditioning (HVAC) facility that needs to be overcome by HVAC equipment (Huang et al., 2015; Yue et al., 2016). Meanwhile, it is a common practice in load design to always consider uncertainties that may arise from service conditions due to load variations (Moser and Folkman, 2008; Liu et al., 2014). This is usually taken care of by 'factor of safety', that is used either to allow future expansion in loads so that the equipment can operate within the safe range or to reduce the possibility of oversizing or under-sizing of HVAC equipment (Ahmedullah, 2006; Gang et al., 2015; Gang et al., 2016; Parameshwaran et al., 2012). The cooling load in this study is calculated as the product of the net heat flux on the soil and a safety factor, given as;

$$\bar{Q}_{load} = \bar{Q}_s \times \gamma$$

Where γ is the factor of safety and $\bar{Q}_s$ is the net heat flux on the soil.

Conduction heat transfer within the soil is considered as the net exchange of kinetic energy by the soil molecules. This usually occurs from a higher temperature region to the lower temperature region (Muerth and Mauser, 2012). However, researches have shown that at any given depth (z) below the surface, the undisturbed ground temperature (T_s^u) follows a periodical/harmonic variation with time as (Novak, 1981; Krarti and Kreider, 1996).

$$T_s^u(z,t) = T_m + T_{am}R_e(e^{iwt})$$

This has been demonstrated in an experiment conducted by a researcher as shown in Fig. 4 (Qin et al., 2002). Thus;

$$\bar{Q}_{cond(i,i+1)} = -k_{s(i)}\frac{\Delta T_{i(t)}}{\Delta Z_i}A_s$$

Where k_s is the soil thermal conductivity, A_s is the surface area of the soil bed and ΔZ is the vertical depth between the top soil and the chilled water pipe, $T_s^u$is the undisturbed soil temperature, T_m & T_{am} are mean and amplitude of the ground surface temperature variations, w is the angular frequency of the periodic variation ($w = 2\pi/day$)

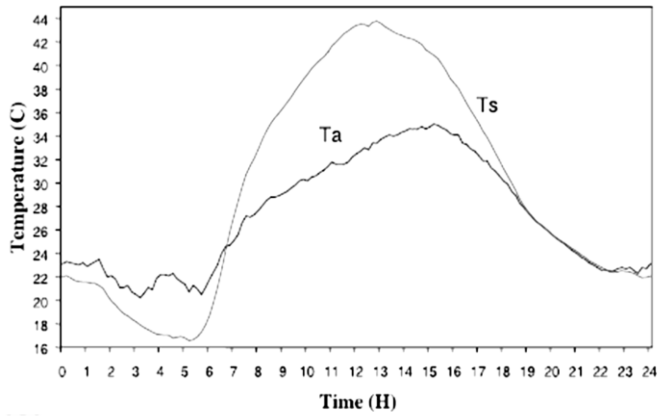


Figure 4: Daily soil and soil temperature profile [31]

2.3 Cooling plant model

An ammonia based vapour absorption refrigeration (VAR) system is the cooling plant considered in this study for chilled water production. The system is designed to operate on low-grade heat such as solar energy using evacuated tube solar collector. Considering solar energy as the heat source for the absorption cooling plant, the effective solar collector size required for absorption refrigeration system has been determined using the following relation (Yeh et al., 2002; Bajpai, 2012; Mumtaz et al., 2016; Singh and Mishra, 2018):

$$A_c = \frac{Q_u}{Q_{inc}}$$

$$Q_u = \frac{Q_b}{k_c}$$

Performance of HVAC system is usually measured in terms of the Coefficient of Performance (*COP*), which relates the cooling output to the energy input for driving the system. In terms of the energy required to vaporize the working fluid, the *COP* is expressed as;

$$COP = \frac{\bar{Q}_{evp}}{\bar{Q}_{boiler}}$$

However, in terms of the overall solar energy available for the system activation, the *COP* is expressed as;

$$COP_{thermal} = \frac{\bar{Q}_{evap}}{\bar{Q}_u}$$

Where; $\bar{Q}_w$, $\bar{Q}_b$, $\bar{Q}_{evap}$, and A_c, $k_c$are the energy received by collector, heat to vaporize working fluid, cooling effect, collector effective area, collector thermal efficiency, and pump efficiency respectively.

2.4 Chilled water flow rate model

The study considers a dimensioned size of soil bed in which chilled water pipe is evenly networked. The passage of chilled water through the network of pipe results in heat transfer due to temperature difference. The temperature difference between the undisturbed soil surrounding the pipe and soil surface causes difference in heat content between soil load (Q_{load}) and chilled water cooling capacity (Q_{sw}). This is otherwise referred to as conduction heat (Q_{cond}), mathematically expressed as;

$$Q_{cond}(t) = Q_{load}(t) - Q_{sw}$$

Therefore, soil temperature corresponding to the optimized chilled water flow rate is expressed in the following equation as;

$$\boldsymbol{T_s^t = \frac{d_z}{k_s A_s}\tau\{Q_{load}(t) - \dot{m}_w C_{pw}\Delta T\} + T_p}$$

Relating the chilled water cooling capacity (with respect to soil bed area) with the cooling plant capacity gives the approximate length of the chilled water pipe. With all specifications appropriately selected, the calculated length of the pipe is evenly networked through the soil bed for even temperature distribution within the soil bed. Table 1 shows the soil bed specifications as used for the experimental soil cooling in this study.

3. Experimental Set-Up

The test rig developed in this study consists of an absorption chiller and the soil bed conducted at the back of Ocean Thermal Energy Centre, Universiti Teknologi Malaysia. Data collected from the set-up include chilled water flow rates and temperatures from the chiller, the soil bed and the chilled water pipes, using T-type thermocouples. The temperatures recorded during the experimental study were logged to the computer hard disk through the National instrument data logger and compared with those obtained from the mathematical models.

3.1 Soil cooling

The soil cooling system consists of two soil beds; cooled soil bed and control soil bed. Each of the soil beds was filled with loamy soil obtained at the experimental site. The chilled water pipe was buried at 0.15 m depth below the soil bed surface (Fig. 5). The properties of the soil and that of the soil bed, and chilled water pipe are shown in Table 1. Type-T thermocouples were used to measure temperatures at 8 points on the set-up (Fig. 7); four on the cooled soil bed, one on the control soil bed, one each on chilled water inlet and return, and one to measure the ambient air temperature.

Table 1: Soil bed and chilled water pipe specifications

Soil bed container		Soil			Chilled water pipe				
Material	Surface area	Type	Thermal cond.	pH	Material	Length	OD	Thickness	Thermal cond.
Polystyrene box	0.25 m²	Loamy	1.5 W/m-K	4.85-5.0	HDPE	1.0 m	0.02m	0.0025m	0.42W/m-K

High-density polyethylene pipe (HDPE) was evenly networked through the soil bed (Fig. 5) and chilled water was pumped through the buried pipe at controlled rate to cool the soil.

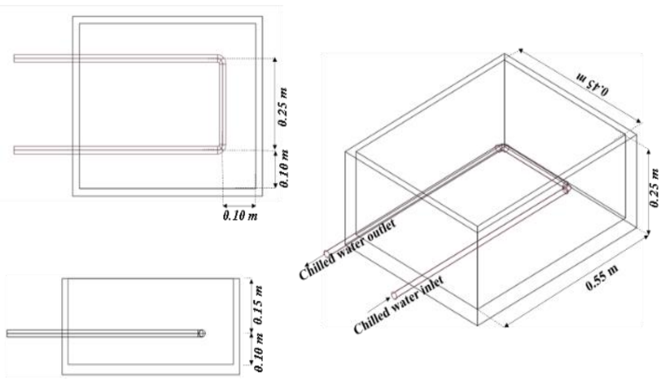


Figure 5: Schematics of the experimental soil bed and piping configuration

3.2 Chilled water production

Experimental investigation of the chilled water production system had been done via a lab-size absorption cooling unit (Fig. 6), taking its operational parameters at steady state to determine its performance characteristics.

Prior to the experimental study, sections of the evaporator, solution heat exchanger, and boiler pipes were insulated against the ambient environment to reduce interference and losses to negligible minimum. Condenser and absorber are air-cooled and were allowed to be fully exposed to the ambient air; the air-cooling of the components was aided by a mini fan with 2.5 W capacity. Chiller's required energy was regulated through its thermostat.

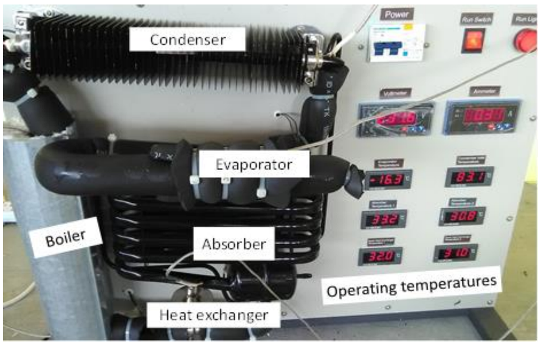


Figure 6: Experimental absorption refrigeration system

3.3 Data collection

The overall set up contained 14 numbers of data collection points; five point on the chiller, eight on the soil beds and one for the ambient air temperature. Chiller's operating temperatures at the boiler, condenser, evaporator, absorber and solution heat exchanger were measured via T-type thermocouples as shown in Fig 7A. The soil bed contained nine data point; one flow sensor for measuring the chilled water flow rate to the soil bed, and eight number of thermocouples for temperature measurement (Fig. 7B). The experimental data were taken for a period of two weeks. Malaysia has a relatively uniform climatic condition over the year hence the period of the experiment is a representative of the annual climatic situation.

3.4 Soil cooling parametric analyses

Assessment of the system performance and its optimization has always been based on investigation of the influence of each of the key parameters (Chen et al., 2017). The effects of air flow rates, and pipe dimension (length, diameter, and thickness) on heat transfer between ground buried pipes were investigated through parametric analysis (Ahmed et al., 2016). In this study, parametric analysis is conducted on the soil cooling process using the response surface methodology (RSM) of the Design Expert® software. Response surface methodology (RSM) comprises of mathematical and statistical analysis tools suitable for defining effects of independent parameters on the output (Hariharan et al., 2013; Ciarrocchi et al., 2017). With RSM, performance evaluation can be made at intermediate levels that might not have been experimentally studied (Hariharan et al., 2013; Rout et al., 2014; Suliman et al., 2017). Central composite design (Custom) of the RSM was used in this study with a 20 number of totally randomized runs to optimize the parameters for the soil cooling model. Apart from the chilled water flow rates, the effects of other influencing factors such as chilled water temperature and ambient air temperatures, on the cooled soil temperature were analysed to gain insight to the extents of their effects on the soil temperature

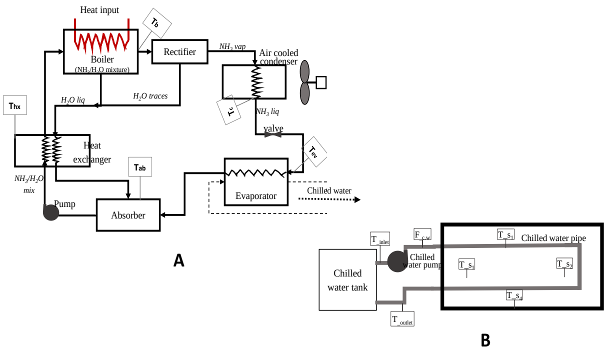


Figure 7: Schematic diagram of experimental set-up with temperature and flowrate measurement

4. Results and Discusions

4.1 Soil cooling performance

The peak load during the daytime has significant effects on the performance of the modelled cooling system (Fig. 8). It is also considered that in the absence of external heat (solar radiation heat) on the soil, its temperature gradient decays over time, leading to a thermal equilibrium within the soil bed ($\Delta T = 0$, thus; $Q_{cond} \approx 0$); and bringing the conductive heat flux close to zero. Considering the climatic condition of the experimental site, modelled soil temperature was studied between 7:00am and 7:00pm during which soil cooling load is at peak due to solar radiation (Fig. 4). Chilled water flow rates between 0.06 kg/min to 0.6 kg/min were selected for the cooling process and their effects were observed for optimal performance in offsetting the peak load. The cooled soil temperature profile (Fig. 8) shows the effects of the midday peak load on the cooling performance.

4.2 Chilled water production

Experimental tests were carried out on lab size absorption chiller, by taking its temperature profiles at different stages to determine its steady state performance characteristics. Chilled water production was achieved from the chiller's evaporator (Fig. 6) whose cooling rates were used to determine the chilled water production rates (Fig. 9). With sets of inlet and outlet chilled water temperature to the evaporator, the mass flow rates of the chilled water were determined with an average flow rate of 0.3kg/hr; keeping the chilled water temperature at the exit and inlet of the chiller are at an average of 5 °C and 10 °C, respectively.

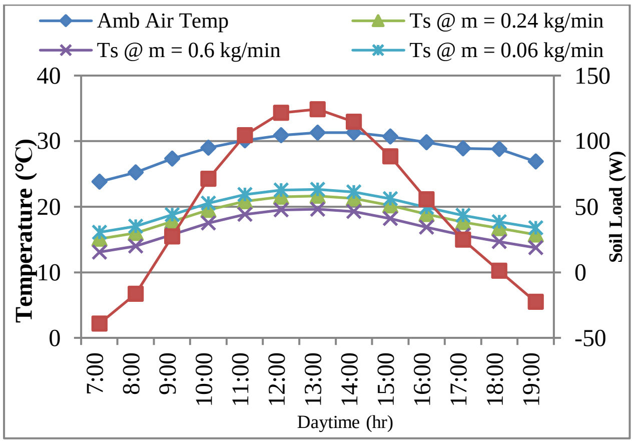


Figure 8: Modelled soil cooling profile during daytime

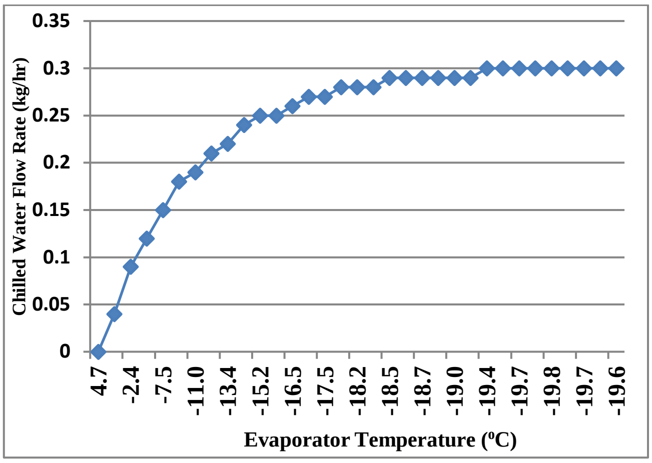
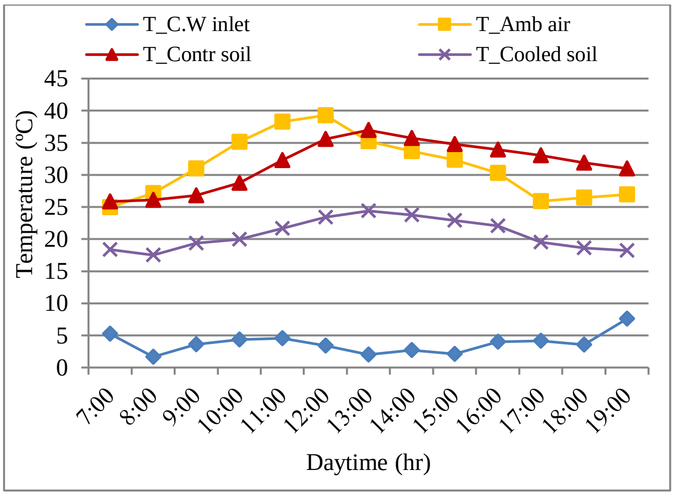


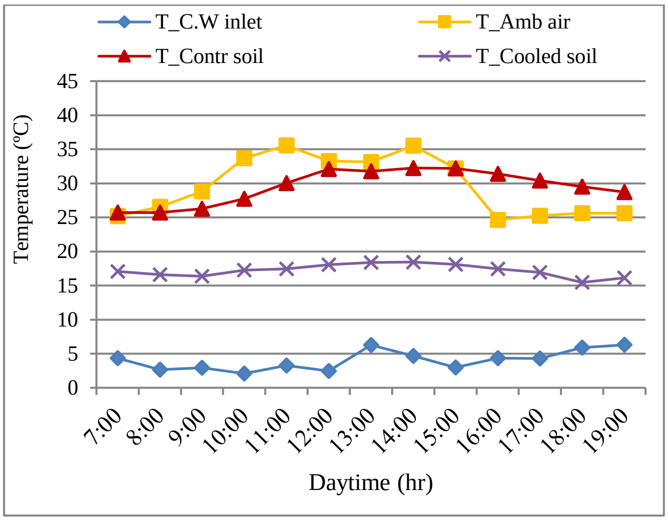
Figure 9: Experimental chilled water flow rate at 5 °C

4.3 Soil temperature profile

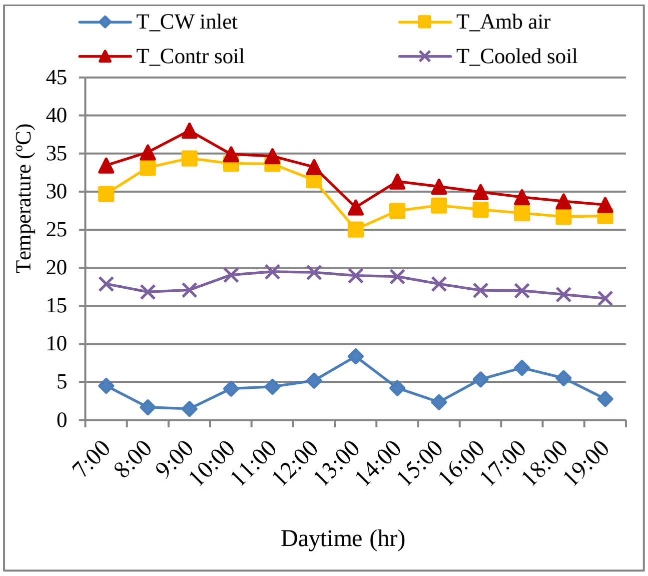
Chilled water temperature to the soil bed was maintained at maximum of 10 °C, while the flow rates were ranged between 0.24 kg/min and 0.6 kg/min for the experimental soil cooling. The effects of chilled water flow rates and ambient air temperature were observed on the cooled soil. Fig. 10 (A-D) show that the selected chilled water flow rates are normally suitable to offset the soil load considering the soil bed size. However, besides the chilled water flow rates and temperatures, the effects of daytime weather condition were observed on the soil temperature profile during the mid-day, when the air temperature and solar radiation are at the peak.



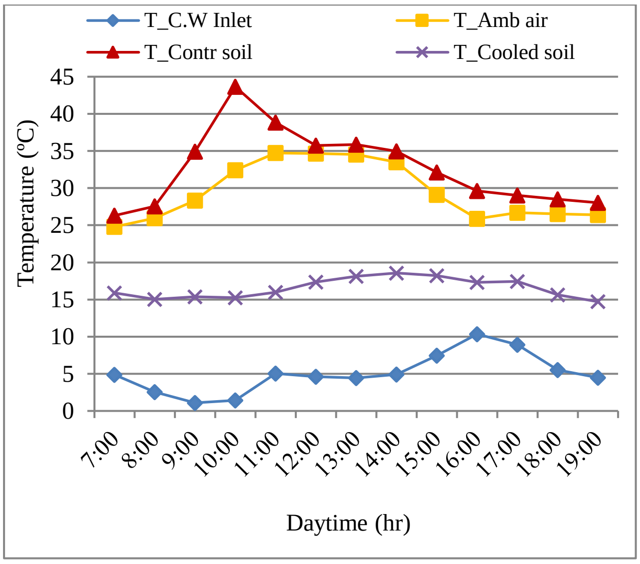
A: (0.24 kg/min)



B: (0.36 kg/min)



C: (0.48 kg/min)



D: (0.6 kg/min)

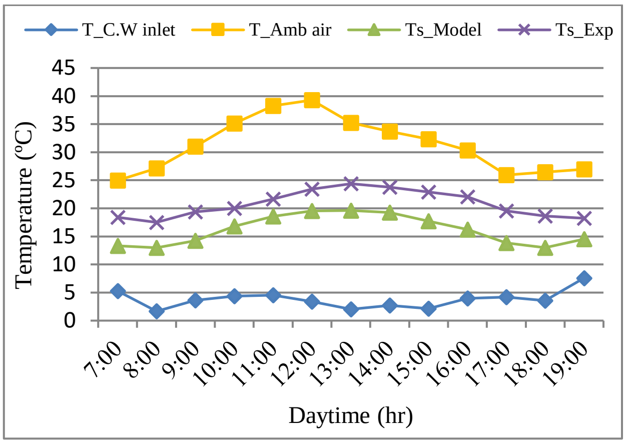
Figure 10: (A-D): Experimental soil temperature profiles

Chilled water application was observed to have significant effects on soil cooling as indicated by wide difference between the cooled soil and control soil temperatures (T_cooled and T_contr, respectively) as shown in Fig 10. It was also observed that all the T_s are at lower range of temperatures starting from 18:00hr, hence chilled water pumping may not be required at night-time to save pumping energy.

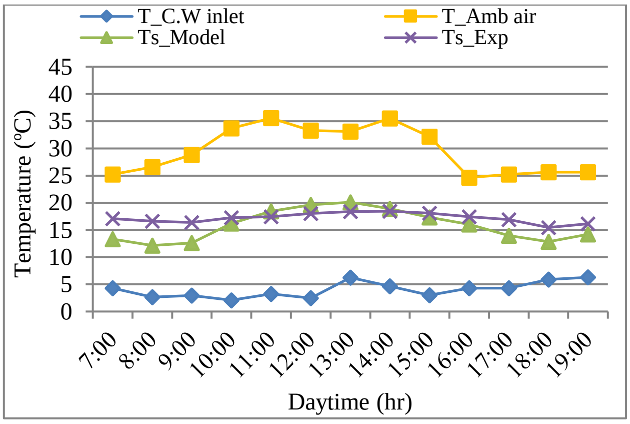
4.4 Model comparison and validation

To check the model reliability, variations between the analytical results and measured values from the experiment have been quantified using the percentage errors and standard deviation under the same conditions.

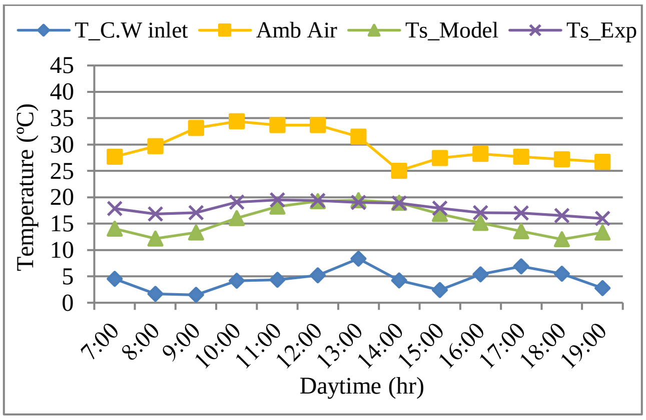
With the chilled water inlet temperatures and flow rates, as shown in Fig. 11 (A – D), both of the experimental and modelled soil temperatures are observed to respond to chilled water flow rates and temperatures, and the ambient conditions of each of the scenarios. It is observed that modelled soil temperatures Fig. 11A are significantly lower than the experimental values. This is observably due to some simplification assumptions in the model and the use of historical climatic data for the peak load analysis. However, results of the model equations and experimental test are reasonably close with average values of the standard deviation and percentage error of 1.75 and 14.24 %, respectively (Table 2)



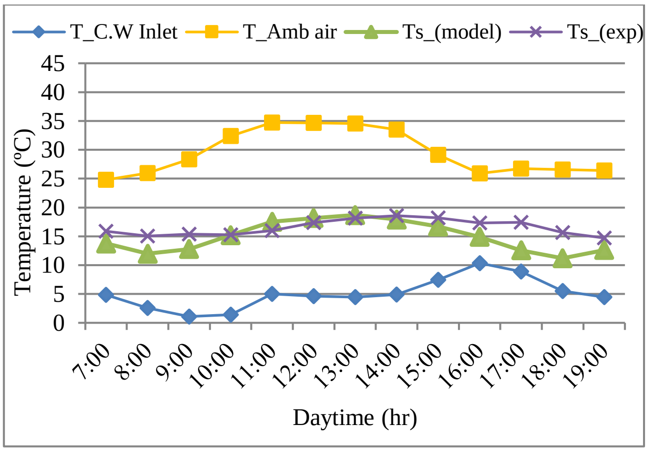
A: (0.24 kg/min)



B: (0.36 kg/min)



C: (0.48 kg/min)



D: (0.6 kg/min)

Figure 11: (A-D): Experimental and modelled soil temperature profiles

Table 2: Experimental and model soil temperature comparison

Time (hr)	C.W Inlet Temp (ºC)	Soil Temp (ºC)		% Error	STDev
		Exp.	Model		
7:00	4.74	17.31	13.61	21.39	2.62
8:00	2.13	16.50	12.32	17.53	2.96
9:00	2.28	17.05	13.24	27.76	2.69
10:00	3.00	17.88	16.06	25.97	1.29
11:00	4.29	18.65	18.18	13.89	0.33
12:00	3.92	19.55	19.15	6.98	0.28
13:00	5.27	19.98	19.47	4.18	0.36
14:00	4.12	19.92	18.76	2.27	0.82
15:00	3.74	19.28	17.14	2.69	1.51
16:00	6.01	18.47	15.58	7.17	2.04
17:00	6.06	17.72	13.49	12.10	2.30
18:00	5.12	16.55	12.26	18.53	3.04
19:00	5.28	16.26	13.66	24.62	1.84
Ave.	4.30	18.09	15.61	14.24	1.75

4.5 Parametric analysis of soil cooling system

Observations of the soil temperatures against the chilled water flow rates shown in Fig. 10 and Fig. 11 indicated that soil temperature is not only effected by the variations in chilled water flow rates but also by the variations in chilled water temperatures and ambient environment. Further analysis of the results was carried out with *RSM* of Design Expert® to assess the extent of the effects of variations of all the three parameters on the cooling performance

The analysis of variance (ANOVA) performed on the interactions of the factors and responses shows that the model is significant, with F and p values of 7.09 and 0.0030 respectively, and "*Lack of Fit*" with p and F values of 2.14 and 0.299. The regression equation developed from the ANOVA for the cooled soil temperature (T_s) is given as;

$$T_s = 17.777 + 0.073\,(A) + 0.318(B) - 466.693 \qquad (C)$$

Where; A, B, and C are the values of ambient air temperature, chilled water temperature, and chilled water flow rates, respectively

The equation above can be used to predict the soil temperature (T_{-s}) at any given condition of ambient air, and chilled water temperature and flow rate.

Model diagnostic plot (Fig. 12) shows the "Lambda value" of 1.61, regarded as the best, with respect to Lambda's low and high values. However, with respect to the size of the experimental soil bed, 0.42 kg/min flow rate is sufficient for the cooled soil temperature can be kept below 19.5 °C, even when the ambient and chilled water temperatures are observably high. Indicating that flow rate beyond 0.42 kg/min may not be required at any time of the cooling process in this particular case (Fig. 13). This indicates that considering the size of the soil bed, 0.42kg/min of the chilled water (5°C – 10°C) will keep the soil temperature at 18 °C ±2 for optimal performance of the temperate crops.

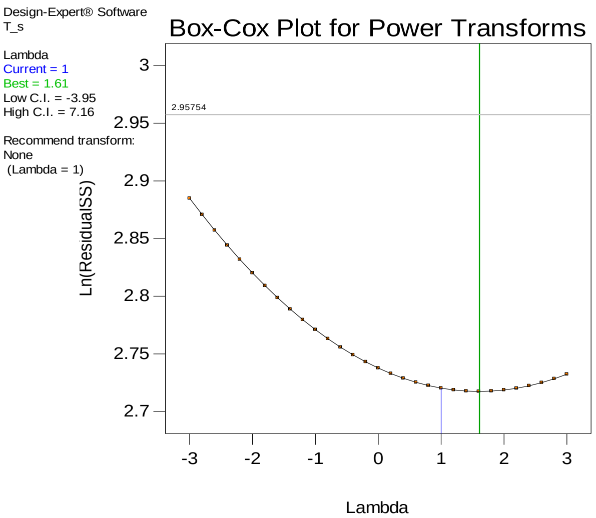


Figure 12: Model diagnostics plots for soil cooling analysis

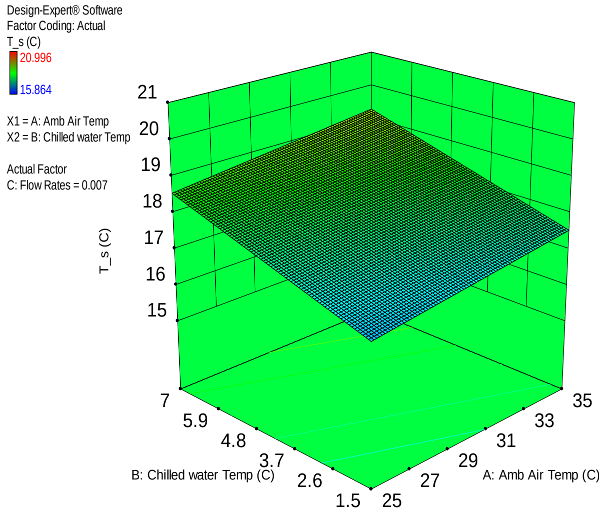


Figure 13: 3-D plots of chilled water and ambient air effects on cooled soil

5. CONCLUSION

Apart from high altitude farming, temperate crops are mainly cultivated in the tropics via the use of cool greenhouses. A more energy efficient soil cooling could be a better alternative and could aid small size home gardening of the high-value crops with appropriate chilled water temperature and flow rates. This process requires right sizing of HVAC equipment for load estimation to be optimally applied. The use of absorption powered by solar energy for this application makes it more economically reasonable. Using various earth-to-air modelling approaches, soil cooling load and equivalent absorption chiller's capacity had been analytically determined with experimental setup conducted to verify the model. The analytical models results have been validated with the results obtained from the experimental set-up. Good agreements were found between the analyses of the results obtained from both the experimental and analytical models. The models agreed well, with standard deviation and percentage error of 1.75 and 14.24%, respectively for the soil cooling. Hence, it could be concluded that the application of this physical model could be extended beyond the experimental size of soil bed in this study with acceptable range of variations. From the parametric analyses, regression equation developed from the ANOVA of the RSM for the cooled soil temperature is suitable for predicting the soil temperature (T_s), given ambient air temperature, and chilled water flow rate and temperature. The *RSM* showed that cooled soil temperature (T_s) is more significantly affected by the chilled water flow rate than ambient air and chilled water temperatures. This shows the feasibility of controlling the soil temperature through the chilled water flow rate. More so, while there is ease of controlling chilled water flow rate and temperature, the ambient air temperature is only controlled by the nature. It has also been shown that maximum flow rate of 0.42kg/min would be sufficient, even during the hottest days to keep the soil temperature at 19.5°C or below which is considered to be the soil temperature range suitable for the temperate crops. This system of application of renewable energy shows the potential for upgrade and substantial contribution to Nigeria national economy.

Nomenclature			
R_n	*Net solar radiation*	$e_a(t)$	*Water vapor pressure at reference height*
Q_{inc}	*Incident solar radiation on the soil*	R	*Ideal gas constant*
$\propto$	*Soil surface albedo*	M_w	*Molar mass of water*
σ	*Boltzmann constant*	A_s	*Surface area of the soil bed*
$\mathcal{E}_s\&\mathcal{E}_a$	*soil and air emissivity*	h_c	*Convective heat transfer coefficient*
T_s & T_a	*Temperatures at soil surface and air*	l	*Length of chilled water tube*
$\bar{Q}_h$	*Sensible heat flux*	r_t	*Inner radius of the chilled water tube*
$\bar{Q}_L$	*Latent heat due to vaporization*	t_p	*Tube thickness,*
ρ_a	*Density of air above the soil*	k_w	*Thermal conductivity of water*
C_{pa}	*Specific heat of air*	N_u	*Nusselt number.*
r_a	*Boundary layer resistance*	U	*Component heat transfer coefficient*
Z_r	*Reference height*	ΔT_{lm}	*Log temperature difference between inlet and outlet fluid*
U_r	*Wind speed*		
K	*Van Karman constant.*	$Q_{load}(t)$	*Cooling load imposed on the soil over the measurement period*
ρ_{v_0}	*Soil surface vapor density*	$\boldsymbol{T_p}$	*Undisturbed soil temperature along the chilled water tube*
ρ_{v_a}	*Water vapor density at reference height*	$\boldsymbol{T_s^t}$	*Soil surface temperature at time t*

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