Potential reduction in water consumption of greenhouse evaporative coolers in arid areas via earth-tube heat exchangers (Postprint)

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Abstract

This study aimed to explore the potential of developing a novel cooling system combining a greenhouse and an earth-tube heat exchanger (ETHE). In this system, greenhouse air is circulated through the underneath soil mass to use the deep-soil cooling effect. This was achieved through the following steps. First, soil temperature profile inside and outside the cultivated greenhouse was monitored for almost one year to study the possibility of using deep-soil coldness for cooling the greenhouse air. Second, a prototype ETHE was built to practically investigate the potential reduction in air temperature as the air flows inside the deep earth pipes. Third, a prototype greenhouse was erected to study the ETHE concept. Results from the first experiment revealed that soil temperature at a soil depth of 2.5 m inside the greenhouse offers good conditions to bury the ETHE. The soil temperature at this soil depth was below the maximum temperature (32°C) that most greenhouse crops can withstand. Results from the prototype ETHE showed a slight reduction in air temperature as it passed through the pipes. From the prototype of the integrated greenhouse and ETHE system, reduction in air temperature was observed as the air passed through the ETHE pipes. At night, the air was heated up across the ETHE pipes, indicating that the ETHE was working as a heater. We concluded from this study that greenhouses in arid climates can be cooled using the ETHE concept which would save a large amount of water that would otherwise be consumed in the evaporative coolers. Further investigations are highly encouraged.

Full Text

Preamble

Title: Potential Reduction in Water Consumption of Greenhouse Evaporative Coolers in Arid Areas via Earth-Tube Heat Exchangers

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Abstract: This study aimed to explore the potential of developing a novel cooling system combining a greenhouse and an earth-tube heat exchanger (ETHE). In this system, greenhouse air is circulated through the soil mass underneath to utilize the deep-soil cooling effect. This was achieved through three main steps. First, soil temperature profiles inside and outside a cultivated greenhouse were monitored for almost one year to assess the feasibility of using deep-soil coldness for greenhouse air cooling. Second, a prototype ETHE was built to practically investigate the potential reduction in air temperature as air flows through deep earth pipes. Third, a prototype greenhouse was erected to study the integrated ETHE concept. Results from the first experiment revealed that soil temperature at a depth of 2.5 m inside the greenhouse offers favorable conditions for burying the ETHE, with temperatures remaining below the maximum threshold (32°C) that most greenhouse crops can withstand. Results from the prototype ETHE showed a slight reduction in air temperature as it passed through the pipes. From the prototype integrated greenhouse-ETHE system, a reduction in air temperature was observed as air passed through the ETHE pipes. At night, the air was heated across the ETHE pipes, indicating that the ETHE functioned as a heater. We concluded that greenhouses in arid climates can be cooled using the ETHE concept, which would save substantial amounts of water otherwise consumed by evaporative coolers. Further investigations are highly encouraged.

Keywords: earth-tube heat exchanger; greenhouse; fan-pad cooling system; water saving; arid areas

1 Introduction

Environmentally controlled agriculture is a major contributor to global agricultural production, particularly in arid environments such as Oman and the United Arab Emirates (UAE), where vegetable consumption rates are increasing alongside rapid growth in the ornamental plant market. The typical Quonset-type greenhouse model available in these regions was originally designed for cold climates to provide a warmer microclimate for plant growth in winter and reduce ambient temperature in summer using cooling techniques. While such greenhouses work effectively in winter, they provide insufficient cooling during the hot summer months in Oman and UAE, leading many farmers to leave their greenhouses unused during summer.

According to UAE statistical data from 2011 (MCCE, 2011), there are 14,777 greenhouses covering 492.5 hm^2 producing vegetables, fruits, and ornamental plants. In Oman, the number of greenhouses has increased rapidly, reaching 782 in 2001 (MAF, 2009), 2,491 in 2008 (Tawfiq and Al-Kaefi, 2009), 4,740 in 2010 (Al-Kiyumi, 2006), and 5,563 in 2015 (Al-Ismaili et al., 2017), representing an annual increase of approximately 40% (Al-Sa' di et al., 2007). Oman, UAE, and other Middle Eastern countries face serious water scarcity problems, with governments partially subsidizing water bills through support programs. In Abu Dhabi, 4% of desalinated water production is consumed by agriculture, while vegetable imports increased from 0.34$×10^{10}$ USD in 2005 to 0.76$×10^{10}$ USD in 2010.

Oman and UAE face the challenge of achieving acceptable food security levels to meet uncertain global food production, safety, and trade conditions while simultaneously conserving their fragile agricultural resource base. Limited natural resources necessitate improved resource use efficiency. Sherif (2009) reported that the UAE agricultural sector includes approximately 8,435 greenhouses producing 0.101$×10^{6}$ t of vegetables, highlighting the importance of protected agriculture in securing and meeting local demands. In Oman, greenhouses have significantly increased cucumber production—the dominant greenhouse crop—with yields up to 24 times that of open-field cultivation (Mazid, 2011). Greenhouse cucumber production accounts for 96.0% of total production. Additionally, some Arabian Gulf countries have undertaken agricultural investments in neighboring countries, though the economic feasibility and sustainability of these ventures remain uncertain.

In arid areas, greenhouses are primarily cooled using fan-pad evaporative cooling systems. However, these systems are water- and energy-intensive. Fadel et al. (2013) reported that an evaporatively cooled greenhouse consumes 0.202$×10^{\{3\}, 10.788×10}\{3\}, and 0.930×10^{3}$ kWh to run irrigation pumps, fans, and cooling pumps, respectively. Additionally, water usage for cooling and irrigation during the production season was 0.838$×10^{6}$ and

0.615$\times10^{6}$ L, respectively. Cooling fans consumed approximately 90.0% of the electrical energy, while the cooling system accounted for about 58.0% of total water consumption during the production season. Similarly, in Oman, cooling water consumption represented two-thirds of total greenhouse water consumption (Sablani et al., 2006). Recent studies found that evaporative coolers can consume up to 75.0% of total greenhouse water demand and nearly 99.5% of electricity consumption (Tabook and Al-Ismaili, 2016; Tabook, 2017). Due to limited water resources in Oman, UAE, and other arid countries, there is an urgent need to develop new technologies that reduce greenhouse water requirements, particularly the amount used in fan-pad cooling systems.

Earth-tube heat exchangers (ETHEs) are extensively used in cold climates to heat buildings by exploiting temperature differentials between indoor spaces and deep soil. ETHEs employ pipes buried underground with a circulation system that forces air through the pipes to mix with indoor air. Air can be drawn either from ambient conditions or from the space being conditioned (Ghosal et al., 2004). This mechanism can be implemented in hot climates to cool the greenhouse microclimate. During daytime, warm air is drawn from the upper parts of the greenhouse and driven through underground pipes. The warm air releases heat to the pipe through convection, which is then dissipated to the soil by conduction, and the cooler air is returned to the greenhouse. Boughanmi et al. (2015) studied the thermal performance of a conic basket heat exchanger coupled with a geothermal heat pump for greenhouse cooling in Tunisia, finding that the maximum average temperature difference between inlet and outlet was approximately 30°C with a mass flowrate of 0.08 kg/s, reducing greenhouse air temperature by about 12°C. Dhruw et al. (2015) reported that ETHEs can achieve 76.7% energy savings compared to conventional cooling systems.

This study aimed to investigate the potential of developing a novel cooling system combining a greenhouse and an earth-tube heat exchanger (ETHE), where the ventilation system would re-circulate greenhouse air through the soil mass underneath the chambers to utilize the cooling effect of deep soil.

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2 Methodology

This study was conducted in three main phases. First, soil temperature profiles inside and outside a cultivated greenhouse at the Agricultural Experiment Station (AES) of Sultan Qaboos University (23.60°N, 58.16°E) were monitored for almost one year to assess the feasibility of using deep-soil coldness for greenhouse cooling. Second, an ETHE was built at the AES to practically investigate potential reductions in air temperature as air flows through deep earth pipes. Third, a prototype greenhouse was erected to study the integrated ETHE concept.

2.1 Soil Temperature Profile

In this phase, the initial task was to measure soil temperature variation with depth. Two pits were dug inside and outside a Quonset-type greenhouse at the AES, which was cultivated with ornamental plants during the experiment. After excavation, thermocouples (T-type, Omega Engineering, USA) and Decagon temperature sensors (Decagon Devices Inc., Pullman, USA) were buried at depths of 0.02, 1.00, 2.00, and 3.00 m as shown in Figure 1 [Figure 1: see original paper]. Data were retrieved and recorded every minute using a datalogger (CR3000, Campbell Scientific, USA).

Fig. 1 Overview of temperature sensor positioning. P1, P2, P3 and P4 represent soil depths of 0.02, 1.00, 2.00 and 3.00 m, respectively, where thermocouples were installed.

2.2 Designing and Validation of a SolidWorks Simulation Model

The primary task in this phase was to simulate and validate the ETHE using a model developed specifically for this purpose. Several mechanical thermal simulation software packages are available for such analysis, including Ansys Engineering Simulation, Pro/Engineering, FEMAP, and SolidWorks. In this study, the modeling code was developed in the SolidWorks 2016 SPO environment. Heat transfer occurs through three mechanisms, but for simplification, conduction and convection were considered while radiation effects were neglected. For the simulation, the heat transfer coefficient was set at 7 $W/(m^2 \cdot K)$, varying with pipe material. In SolidWorks, a soil block measuring 8.0 m long, 3.0 m wide, and 4.0 m deep was modeled. Steel and drainage pipe networks with a diameter of 0.1 m and spacing of 1.4 m were simulated to match the intended practical setup, as shown in Figure 2 [Figure 2: see original paper].

To validate the simulation model, we constructed a pit measuring 6.0 m long, 3.0 m wide, and 2.5 m deep. Steel and drainage pipes (diameter 0.1 m, length 6.0 m) were laid at the bottom of the pit and connected to 3.0 m long vertical pipes. Experiments were conducted at different inlet air velocities using a suction fan setup capable of varying air speed from 3 to 10 m/s (Fig. 3 [Figure 3: see original paper]). Experiments were performed at air speeds of 3, 5, 7, and 9 m/s. T-type thermocouple wires measured air and soil temperatures within and outside the two pipes, with a Campbell Scientific CR3000 datalogger collecting temperature data from all thermocouples.

Fig. 2 SolidWorks modeled pipe networks (a) and soil block assembly with pipe network (b)

Fig. 3 Fan-mounting structure

2.3 Construction of the Prototype Greenhouse and ETHE System

Based on results from previous phases, parameters for the prototype greenhouse and ETHE system were determined. In this setup, the ETHE consisted of 13 drainage pipes (diameter 0.1 m, PVC material) connected directly to a fan (diameter 0.85 m, 0.55 kW motor, 1400 r/min) and buried at a soil depth of 2.0–3.0 m below the greenhouse. Figure 4 [Figure 4: see original paper] illustrates the design model and construction process of the prototype greenhouse and ETHE system at the AES. The greenhouse was covered with a polyethylene sheet (thickness 0.2 mm) on the roof and double-layer polycarbonate on the sidewalls. After construction, Omega thermocouple wires monitored temperature changes across the model greenhouse (floor area 6.0 m $\times$ 3.0 m) and ETHE units. One thermocouple was placed at the greenhouse inlet and another at the outlet (fan side) (Fig. 5 [Figure 5: see original paper]). The greenhouse inlet corresponds to the ETHE outlet and vice versa. For data recording, a Campbell Scientific CR3000 datalogger was programmed to retrieve and record data every 30 seconds to avoid instantaneous fluctuations and outlier readings, ensuring smoother patterns.

Fig. 4 Designed model of greenhouse and ETHE (earth-tube heat exchanger) system (a), ETHE installation (b), greenhouse framework after refilling the ETHE trench (c) and completed prototype greenhouse and ETHE system (d)

Fig. 5 Locations of the shielded thermocouples at the inlet (a) and outlet (fan side; b) of the greenhouse

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3 Results and Discussion

3.1 Soil Temperature Profile

Results from the first experiment revealed that soil temperature at all depths (0.02, 1.00, 2.00, and 3.00 m) outside the greenhouse (under bare soil) did not provide suitable conditions for burying the ETHE for cooling purposes. However, soil temperature at depths of 2.00–3.00 m inside the greenhouse offered suitable conditions, as temperatures at these depths remained continuously below 32°C —the maximum tolerable temperature for high-value vegetable crops (Black and Drost, 2010). Soil temperatures at almost all depths in the pit outside the greenhouse exceeded 32°C. Figure 6 [Figure 6: see original paper] depicts the soil temperature profiles observed over several months inside and outside the greenhouse. Deep soil inside the greenhouse was cooler than soil outside because it benefited from cool air streaming over the soil surface and shade created by the greenhouse covering material. Additionally, the soil was further cooled by irrigation water, which removed sensible heat through evaporation—conditions absent in the bare soil outside the greenhouse.

Fig. 6 Mid-day soil temperatures for the pits outside (a) and inside (b) the greenhouse. P1, P2, P3 and P4 represent soil depths of 0.02, 1.00, 2.00 and 3.00 m, respectively. The red dotted line indicates the maximum tolerable temperature (32°C) for high-value vegetable crops.

3.2 SolidWorks Simulation Model

Based on the previous results, we inferred that the optimal soil depth for laying the ETHE is between 2.00 and 3.00 m. Accordingly, a 2.50 m deep trench was excavated to bury two pipes (metallic and plastic) with a diameter of 0.10 m to function as ETHEs. This setup was simulated using a SolidWorks flow simulation model that was subsequently validated with experimental data. Iterative simulation trials showed a very close match between observed and simulated air temperature values, revealing a slight reduction in air temperature as it passed through the pipes with negligible differences between the two pipe materials. Air cooling was adversely affected by air speed—less cooling occurred at higher velocities. Figure 7 [Figure 7: see original paper] shows mid-day and mid-night simulated and observed air temperature profiles along one pipe at an air speed of 3 m/s, chosen because preliminary experiments indicated that 3 m/s produced better cooling effects compared to 5, 7, and 9 m/s (not yet published). Given the simulation accuracy demonstrated in Figure 7, the model was used to simulate thermal behavior of single pipes and pipe arrays buried in the ground, as illustrated in Figure 8 [Figure 8: see original paper]. These thermal patterns showed that heat from the air dissipates gradually into the soil while soil temperature remains below the 32°C threshold, confirming ETHE feasibility for greenhouse cooling. Finally, we decided to use 13 plastic pipes in the ETHE pipe network.

Fig. 7 Observed and simulated air temperature inside the earth-tube heat exchanger (ETHE) pipe at an air speed of 3 m/s

Fig. 8 Temperature distribution pattern around the ETHE pipe network composed of one pipe (a) and arrays of three (b), seven (c) and eleven (d) pipes. These patterns are taken at the middle of 6.00 m long ETHE pipes.

3.3 Prototype Greenhouse and ETHE System

Based on results from phases 1 and 2, we buried the ETHE pipes at a soil depth of 2.00–3.00 m below the greenhouse. Figure 9 [Figure 9: see original paper] presents a 2-day air temperature profile along the middle pipe of the ETHE, with ambient air and soil (3.00 m depth) temperatures shown for comparison. During mid-day, the ETHE received the warmest air from the greenhouse, which was cooled as it passed through the underground pipe network. Conversely, the ETHE received cool air at mid-night, which was heated when passing through the pipes. Soil temperature at 3.00 m depth remained almost constant throughout the daytime, indicating that the soil had excellent thermal capacity to absorb heat from the greenhouse during the day and release it back at night. Further optimization is required to increase ETHE effectiveness, particularly for daytime operation.

Time series data were analyzed to better understand the cooling effect. Six-hour average data were used to calculate temperature differences across the greenhouse (outlet minus inlet) and the ETHE (inlet minus outlet), presented in Figure 10 [Figure 10: see original paper]. All greenhouse and ETHE temperature differences were positive during daytime but negative during nighttime. For the greenhouse, positive temperature differences during daytime resulted from solar heat input that decreased from mid-day onward. For the ETHE, outlet temperature was lower than inlet temperature during the day, indicating successful cooling, while outlet temperature was higher than inlet temperature at night, demonstrating that the ETHE functioned as a heater during nighttime.

Fig. 9 ETHE temperature variation of air, soil and inside the ETHE pipe for a 2-day period. Env, temperature of air; In avg, average inlet air temperature to the ETHE; Out avg, average outlet air temperature from the ETHE; Soil (3.00 m), soil temperature at a depth of 3.00 m.

Fig. 10 Temperature differences through the greenhouse (outlet minus inlet) and the ETHE (inlet minus outlet) during daytime (12:00–18:00) and nighttime (00:00–06:00) for a 2-day period

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4 Conclusions

This study explored the potential of cooling greenhouses via earth-tube heat exchangers to reduce water consumption in arid areas suffering from chronic water scarcity. We conclude that soil temperature at depths of 2.00–3.00 m inside a cultivated greenhouse remained continuously within the cooling requirements for most vegetables throughout the year, indicating that the ETHE concept should work effectively underneath cultivated greenhouses. Consequently, ETHE systems can save substantial amounts of water currently used in evaporative coolers. We recommend implementing ETHE systems underneath cultivated greenhouses to benefit from the soil-cooling effect exerted by the cold environment inside the greenhouse. Further investigations are necessary in arid areas to optimize system performance.

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