Testing the Potential for an Earth Tube and Water-to-Air Heat Exchanger System for the Cooling and Heating of Greenhouses

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Abstract

The efficacy of an earth tube used conjointly with a water-to-air heat exchanger for greenhouse environmental control was tested in Riverside, CA. Greenhouses by their nature with large surface area and minimal insulation to block thermo radiation make temperature maintenance difficult when ambient temperatures are outside the optimum range. The air within the test greenhouse, a small 2.13 m x 2.13 m x 3.66 m (7' x 7' x 12') reinforced nylon mesh vinyl-covered unit, was drawn in through one end of the earth tube and blown out the opposing end, then moved through a water-to-air heat exchanger to aid in greenhouse temperature management. Pumped water from a well went through the water-to-air heat exchanger, delivering the heat transferable charge to reduce/increase the thermal load of the greenhouse. The earth tube placed 2.44 meters (8 ft) below the surface offered additional heat transfer to further assist with an ideal greenhouse environment. The study demonstrated that an earth tube combined with a water-to-air heat exchanger achieved a temperature drop between air entry and exit points of about -1.1°C (30°F) on an August day with outdoor temperature of 41.1°C (106°F).

Literature Review/Introduction

The cooling and heating of greenhouses can be expensive and difficult to control in areas where ambient temperatures fall far below or high above the desired in-house temperatures. Modern greenhouse cooling/heating methods may include ventilation, fan and pad, fog cooling, and convection tube cooling (Nelson 2003). These systems all serve to control in-house temperatures, but may not conserve resources like electrical energy, or, particularly, water that is a precious commodity in arid regions. The use of earth tubes and water-to-air heat exchangers may mitigate portions of the considerable cost for environmental control. Ghosal and Tiwari (2006) state that heating and cooling of a greenhouse is one of the most energy-consuming operations for protected cultivation.

Many researchers have examined the use of Earth-Air-Heat-Exchangers (EAHE), or earth tubes, to aid in transferring heat from greenhouses and other structures by moving hot air underground through a buried pipe. Sharan and Jadhav (2003) tested a single pass earth-tube in Ahmedabad, India, and achieved a significant temperature drop (stated as much as 14°C/ 57°F) in the warmest season for that area. Sethi and Sharma (2008) surveyed and evaluated all of the traditional heating/cooling systems used worldwide for greenhouses, but the possibility of water-to-air heat exchangers was not addressed. Levit, Gaspar, & Piacentini (1989) conducted an earth tube heat exchanger study in Argentina, where producers typically burn coal to heat, and either whitewash or openly ventilate their greenhouses for cooling. In a 1995 review of literature regarding passive heat transfer, Jacovides and Mihalakakou stated that earth-to-air heat exchangers contributed significantly to buildings' and greenhouses' energy needs. Bojic, Papadakis, & Kyritsis (1997) tested a two pipe system that allowed for heated air to be used in the winter, and cooled air for cooling during the summer. Their study did not involve a greenhouse but supports the premise that earth-to-air heat exchangers can be used for many purposes. In another study, Sethi and Sharma (2008) tested and proved the ability for an aquifer-cooled air tube to aid in the cooling/heating of a greenhouse. Their project demonstrated that water used from underground sources can heat or cool a greenhouse.

Mankind has attempted to control environmental conditions dating back to prehistoric times. Soil temperatures just a few feet below the surface can be 10-18.3°C (50-65°F). The heating and cooling capabilities of the earth can be used to control greenhouse temperatures. Just as canines dig shallow wells into the soil and lay in the cooler soil below the surface for comfort, that same concept can be utilized to cool water flowing through pipes, which can be routed through a heat exchanger. The temperature of the water pumped from a well at a depth of 13.7 meters (45 ft) can be 12.8-21.1°C (55-70°F) or lower.

This project tested a heating/cooling tube (earth tube) and a stacked (multiple unit) heat exchanger for the control of greenhouse temperatures inside a small 2.13 m x 2.13 m x 3.66 m (7’ x 7’ x 12’), light-duty unit. The two methods were utilized in combination. A water well, 15.2 meters (50 ft) deep, with a flow rate of 7.6 liters (2 gal) per minute, provided the heat exchanger with a heat transfer solution that could either heat or cool depending on the ambient conditions. A 30.5 meter (100 ft) earth tube of 152.4 mm (6 in) internal diameter was installed 2.4 meters (8 ft) below the surface with ends terminating inside of the greenhouse (Photo 1). Air blown into the tube from within the greenhouse absorbed or gave off heat, depending on the temperature of the incoming air. The earth tube had an electric fan installed on either end, one blowing into the tube and one extracting air from the tube. The tube itself was a corrugated drain pipe made of polyethylene.

Photo 1

Materials and Methods

The project tested the efficacy of well water pumped through a heat exchanger/fan arrangement, used in conjunction with a fan-forced earth tube, to heat and cool a greenhouse. A solar-powered pump delivered well water during daylight hours. The typical summer pumping cycle was up to eight hours, while winter pumping cycles could be 0-5 hours with shorter days and rainy/cloudy weather. Once the water left the heat exchanger, it was delivered to a drip irrigation system that provided daily water to about thirty Washington Navel orange trees. A closed-loop recirculation system or a return of heated water to the well could have been used if irrigation of nearby plants was not required.

A 152.4 mm (6 in) diameter corrugated polyethylene earth tube, manufactured by Advanced Drainage Systems, was installed at a depth of 2.4 meters (8 ft) over a length of 30.5

meters (100 ft). Two 24-volt axial fans (manufactured by Ebm-papst Inc. in Farmington, CT), installed at either end of the tube, moved air through the tube, one installed for pushing and the other for pulling. The fans were rated at a flow of 283 cubic feet per minute. The tube had ¾" gravel poured around the circumference to aid in heat transfer. Ambient air (inside the greenhouse) was blown through the tube with an axial fan and pulled through the pipe with a matching fan.

An Enviro-Alert controller from Winland Electronics Inc. automatically switched fans based on readings from temperature sensors. The Enviro-Alert EA400, an automatic environmental alarm monitor, switched fans and water valves on and off for automated temperature control. The unit allowed the attachment of four temperature sensors that reported conditions within the greenhouse. The EA400 was programmed with a high temperature activation point of 29.4°C (85°F) and the low set point was 7.2°C (45°F). The heat exchanger utilized two axial fans for air movement, while the earth tube had one axial fan at each end of the pipe.

Power for the EA400 and axial fans was generated by two 24-volt solar panels that delivered over ten amps. The system also utilized four Absorbent Glass Mat (AGM) batteries that stored electrical energy for operation when there was low or no output from the solar panels.

The EA400 required a 12-volt power source for proper function. To accommodate this need, a 24-volt to 12-volt converter was employed (Pyle Audio PSWNV720 24V DC to 12V DC). All fan circuits were fuse-protected. The electrical system included four batteries, Xantrex 40 ampere solar charge controller, Winland EA400, Bosch single pole relays, Blue Sea Systems ST Blade Fuse Block, 24-12 volt converter, positive buss bar, negative buss bar, and wiring required for connecting all components. The solar panels were mounted directly above the system described.

Two light duty (reinforced vinyl cover) 2.13 m x 2.13 m x 3.66 m (7' x 7' x 12') greenhouses were assembled and used for testing. One greenhouse served as an experimental unit with earth tube and heat exchanger cooling. The second greenhouse (control) was monitored for static temperature with no cooling assistance.

Data loggers were placed in similar areas of each greenhouse in order to make reliable comparisons regarding temperature and humidity. The data collection devices, about the size of a lipstick tube, could be easily moved anywhere in the greenhouse. The data loggers were programmed to monitor for a single 24-hour cycle or up to 333 days. The data recording units installed in the greenhouses were set to record up to 41 days with 2000 points of data saved at a rate of once for each half-hour.

The heat exchanger consisted of a plywood enclosure and automotive radiators for heat-transfer testing. The radiators were separated by approximately 304.8 mm (12 in) to allow access to pipe/hose/fan connections. Two axial fans moved air through the heat exchanger assembly. The radiators were sealed into the plywood enclosure with expanding spray foam.

Temperature Recording

Data were collected from two data loggers installed in similar areas of the two greenhouses. The data logger in the test greenhouse was positioned in the air stream from the heat exchanger; the one in the control greenhouse was put in the corresponding zone (midsection, waist-high, right side). Two-thousand data points were recorded once every 30 minutes over a 41 day period. The data loggers were then removed temporarily from the greenhouses for downloading of the data.

A sampling of data logger values from the greenhouse with earth tube and heat exchanger can be seen in the following figures and appendix. For ease of comparison, the test unit temperatures are shown as blue and control unit as red.

Results

Warm Weather Data

Figure 1 shows a typical decrease in temperature (test unit) for a hot day. The ambient day time temperature exceeded 41.1°C (106° F) on 8/25/11.

The data in Figure 1 reveal the environment with the earth tube alone between 9:48 am and 10:18 am before the solar-powered well pump had sufficient light to deliver water. However, from 10:48 am until 5:18 pm, a clear difference of temperature data is displayed as the water-to-air heat exchanger joined in to mitigate greenhouse temperature. While the temperatures displayed are still quite warm for greenhouse plants to be grown, the temperature of the building could be further cooled with shade cloth, whitewash, or pad and fan methods of temperature control. The water-to-air heat exchanger would also deliver increased temperature control if higher water flow rates were available to assist in transfer of heat.

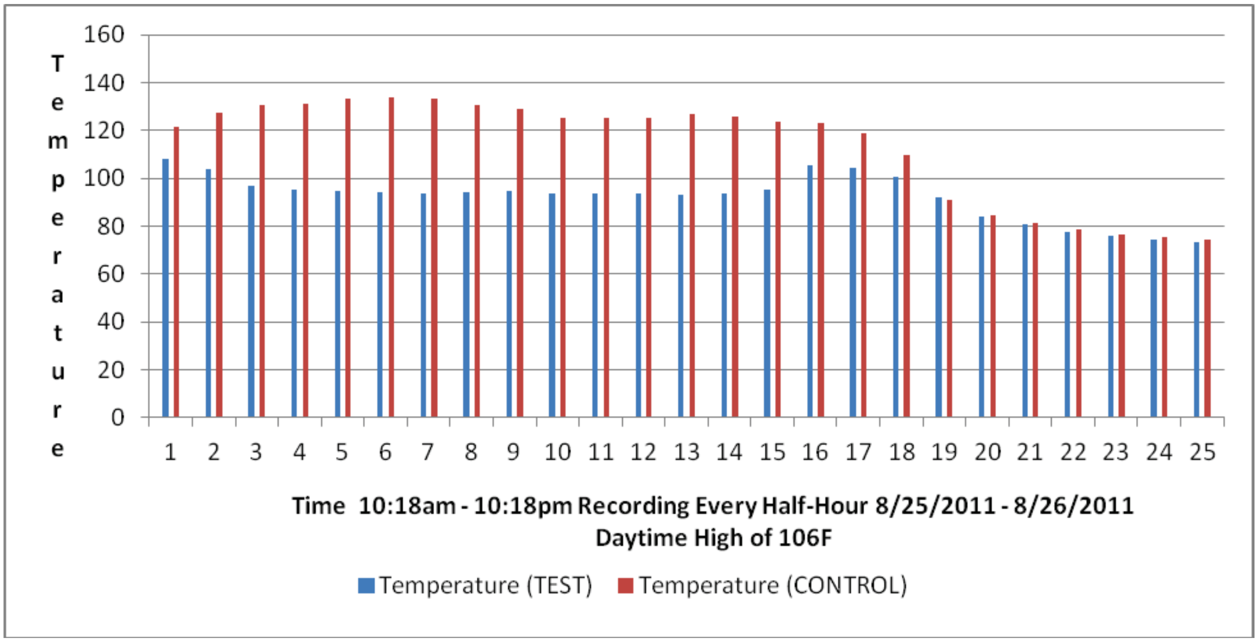

Figure 1

Figure 1 compares data from the two houses. The test unit (blue) data reflect the earth tube and water-to-air heat exchanger system's ability to control greenhouse. Data points 19 through 25 illustrate the temperatures after the control system was turned off automatically by the EA400 because in-house temperatues reached 85°F and lower. Temperature data from the greenhouse with no treatment (control unit) are shown on the same date with correlating times (red). These data reveal the natural condition when high temperatures and low humidity act on non-cooled greenhouses.

On July 3, 2011, the EA400 reported a top-of-greenhouse temperature of 53.3°C (128°F) with both the heat exchanger and earth tube systems operating, and delivering an air charge that was 27.8°C (82°F), 7.8°C (46°F) cooler (data not shown, unpublished).

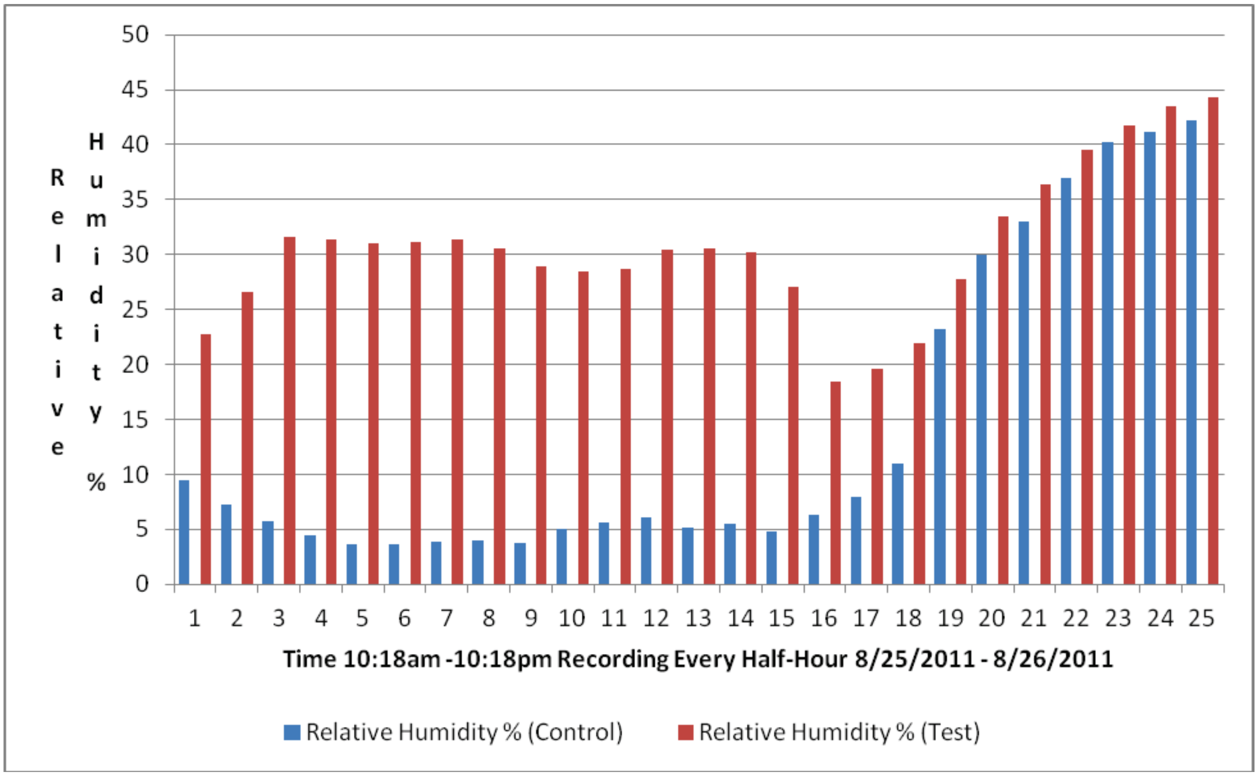

Figure 2

The data logger also recorded humidity, which is shown in Figure 2. The relative humidity (RH) in the test greenhouse was between 28.5% and 31.4%. This demonstrated that the cooling system may help to maintain greenhouse humidity levels when compared with the control (blue) unit showing a value of 6.1% RH at the highest point until afternoon cooling set in. These data are also from the date of 8/25/2011 with a daytime high of 41.1°C (106°F). Humidity control in the greenhouses was not of particular interest in this study because the primary project objective was to control temperature.

Cold Weather Data

Cold weather data was difficult to record in Southern California due to the rare incidence of frost or below freezing temperatures. However, early November 2011, offered an unusually cool weather event which allowed for the recording of greenhouse conditions with ambient temperatures near freezing. The data below were recorded from the test unit.

The data in Figure 3 demonstrate the ability of the installed system to help buffer the greenhouse environment against very cool outside temperatures. Temperatures on the night of November 5, 2011, were just above freezing, and some subsequent frost damage of leaf edges was seen on juvenile avocado trees, which are especially susceptible to near freezing and below temperatures. The ability for this system to be fully-tested against cold weather cannot be established in Riverside, CA, due to the temperate climate, where temperatures below 32°F are rarely seen. Futher testing of this project could be held in other locations where climates are colder, perhaps in areas of the Eastern United States.

The graph in Figure 3 demonstrates the heating potential of the installed system. Data clearly show that some heat transfer into the test greenhouse (blue) can be achieved from the use of an earth tube and water-to-air heat exchanger system. The severity of the low temperature night of November 5, 2011, is shown in Figure 3. The control greenhouse (red) clearly is affected by outdoor conditions.

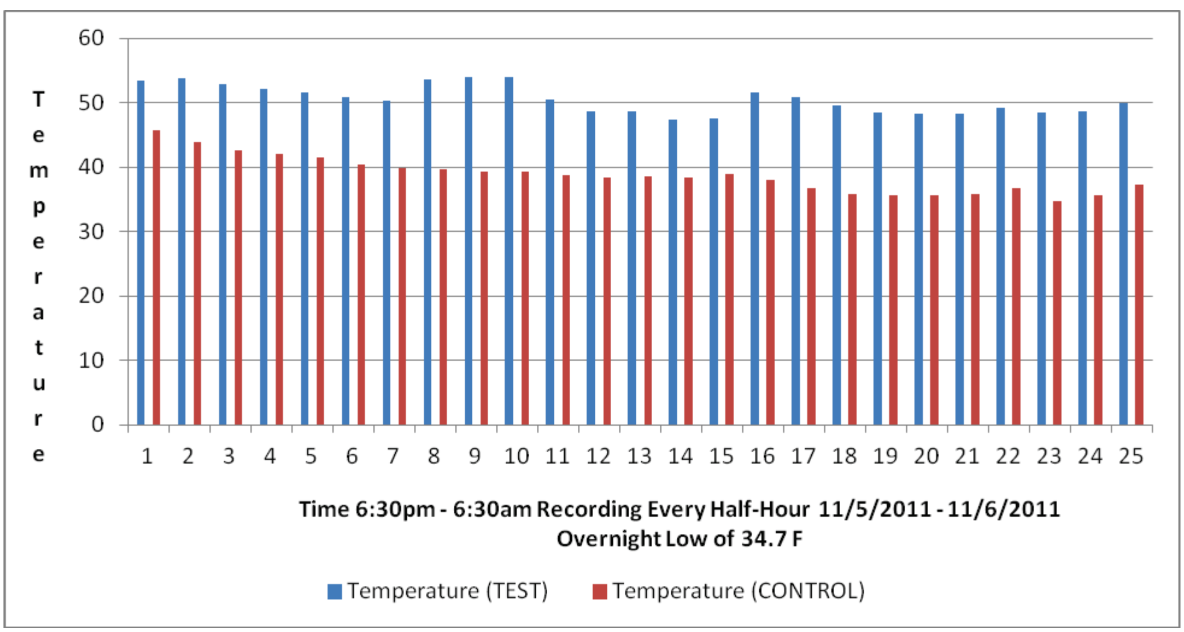

Figure 3

Discussion

Sharan and Jadhav (2003) were able to achieve a temperature drop of 14°C/57°F in their 10cm (4 inch) by 50 meter (164 foot) earth tube. They used a 400-watt fan to force air through the tube. The earth tube used in this study did not achieve the temperature drop of the Sharan and Jadhav study, but did have approximately a -1.1°C/30°F drop (unpublished data) between the inlet and outlet of the earth tube. The two fans on the author's earth tube were rated at 26-watts and could not move the amount of air that the fan in the Sharan and Jadhav study did. The author chose the lower-wattage fans as a means to conserve electrical energy. Sharan and Jadhav buried their earth-tube at a depth of 1.8 meters (5 '11"), more than two-feet shallower than that in the author's study. The depth of the earth tube may not be a contributing factor in temperature transfer. The type of soil, the length of the pipe, ambient temperature, and the power of the fan were likely significant factors. In their survey and evaluation of greenhouse cooling systems, Sethi and Sharma (2008) listed a study done in France where a double row of earth tubes was utilized. The system was able to cover 62% of the heating needs of a greenhouse growing potted plants. The author's earth tube system did decrease temperature between the inlet and outlet of the pipe, but the greatest control and transfer of heat for the study was rendered by the water-to-air heat exchanger, estimated at 80% of total heat transfer.

The earth tube/water-to-air heat exchanger system could be utilized on a variable cost scale with large water-to-air heat exchangers placed in key locations in large greenhouses. The solar-powered aspects of the proposal could easily be driven through a typical grid-based electrical supply. The system could also be used in conjunction with most of the other types of greenhouse environmental control systems such as evaporative cooling. A future study could examine a closed-loop system with tubing (buried), pump, coolant solution, and heat exchanger for greenhouse environmental modifications; since a recirculation system would be used, there would be no wasted resources in the case of arid environments.

The project was conceived because of a combination of factors. During frost protection of orange groves, growers run irrigation to provide a protective layer of ice. The ice releases some of its heat to the trees, shielding them from the ambient temperatures of -2.2°C (28°F) or lower. A proposal to use the relatively stable temperature of the soil to act as a warmer for each tree without the expense of water was rejected because the cost to heat over 200 acres of citrus would be cost-prohibitive. Cost was also an aspect considered when two water wells were drilled and developed for irrigation to over 50 fruit trees. Interest in using renewable resources and saving money on electric bills led to discussions with solar companies, which resulted in the installation of a photovoltaic system for home power. While talking to other greenhouse growers in Riverside, CA, it became apparent that constructing a small greenhouse to start transplants before the frost-free date would be beneficial. Blending these factors into one venture became the project plan.

Location of the test greenhouse was determined by proximity to the water well and maximum exposure to the sun. Once established, the backhoe excavated a C-shaped trench to 8 feet, the maximum depth it allowed (Photo 2). Cave-ins of the 80’ long trench were prevented by using a twelve-inch bucket, which was sufficiently wide for the earth tube. Two short utility trenches were dug: one from the well, and the other from the shed, to what would become the interior of the structure. Irrigation pipes and valves were installed in the one, and electrical wiring was run in the other. Then several yards of ¾” gravel were put into the bottom of the trench, the earth tube was snaked onto the gravel, more gravel covered the tube, and the dirt was moved back into the trench, covering the newly-installed tube, irrigation pipes, and wiring.

Photo 2

Some of the greatest challenges to the success of this project were realized in the design and assembly of the electrical system. With 30 plus years involving technical repair of automobiles, the author's abilities, as related to low-voltage (12 – 24 volt) circuitry, are well beyond that of the layman. The ability to imagine the 12-volt layout and connections was simple at first, but proved to be less-than-ideal in practice.

The two solar panels used for the system were donated from SolarMax Technologies, Inc. (www.solarmaxtech.com). They were from different manufacturers, and their open circuit voltage outputs differed also. One had 30-volts direct current (DC), while the other had a 36-volts DC delivery. This higher-than-expected voltage meant reworking the 12-volt function for all systems, which then required a 24-volt application for relay input and output, fan power, battery wiring, solar charger reconfiguration, and water valve function. The 12-volt system was still needed for the EA 400, relay switching, and lighting. This fact required the purchase of an additional 24-volt-to-12-volt converter. Although this added work and expense was unwanted, not all of the aspects of adding a dual-voltage system were bad: 24-volt fans are far more energy-efficient than their 12-volt counterparts, meaning that significant electrical energy conservation was realized. A functional restart occurred after reassembling the electrical system into dual-voltage, installing new fans and voltage converter, and conducting final testing and setup.

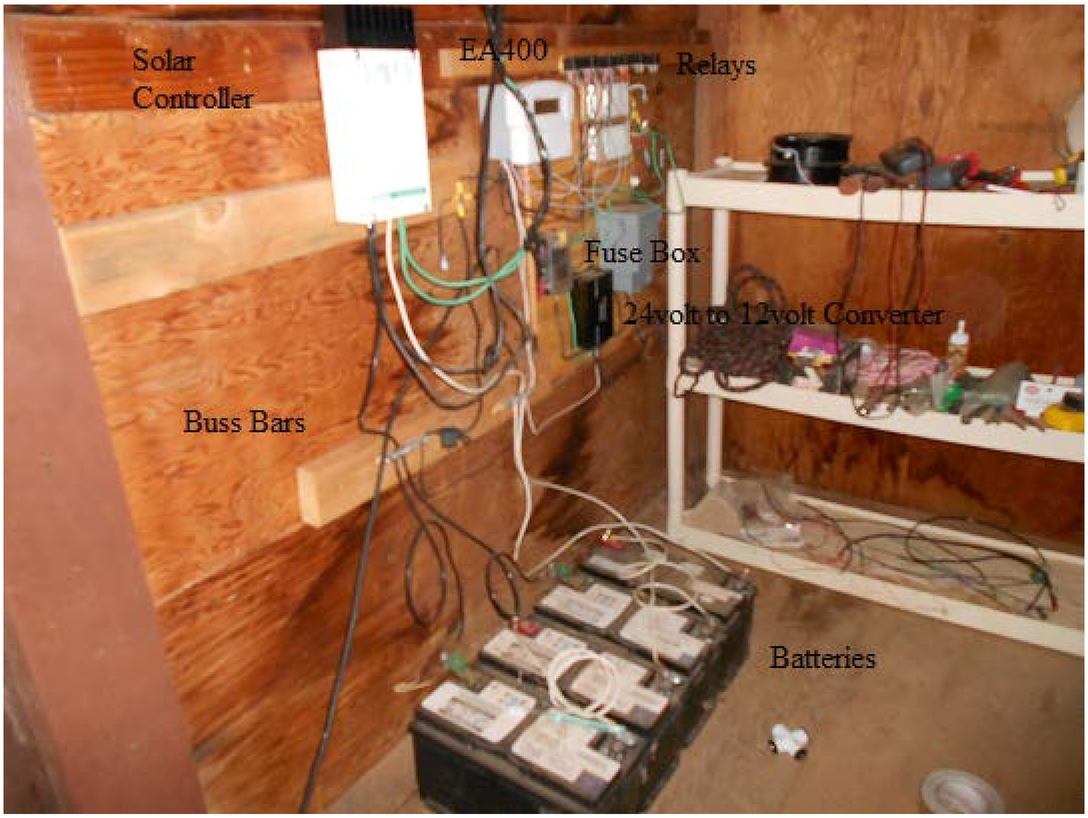

Photo 3

Some other decisions needed to be made before officially beginning the project. The first concerned location of the control greenhouse. By moving ten feet southwest of the test unit, the control greenhouse could enjoy the same sun exposure as the test greenhouse without shading it.

Next, settling on the use or exclusion of other methods for cooling, such as whitewashing and covering greenhouses with shade cloth, was considered. To test whether the earth tube and water-to-air heat exchanger system could be used as a viable environmental control, other techniques were not included in this study. In a commercial greenhouse business, cooling would be optimized by utilizing conventional low-cost technologies in conjunction with the experimental earth tube and water-to-air heat exchanger system.

The earth tube and water-to-air heat exchanger system would benefit from one more solar panel and two more batteries, thereby making the system reliable for longer periods of cold weather with cloudy days. The fixed aspect of the solar panels had been discussed. For future use, it has been determined and planned to utilize a hydraulic tilting system (to be designed by the author) to pivot the panels toward the rising sun until noon, and then tilt them back to the rest area they have occupied for the duration of this project. The tilting panel design may allow for up to two more hours of solar-powered pumping each day, delivering earlier conditioning of greenhouse temperatures and increasing output to the cultivars on the outgoing side of the water-to-air heat exchanger.

Expense of Implementation and Questions

The expense of this type of system is quite variable, depending on the level of equipment available, soil type, number of solar hours available, ambient environmental conditions, water sources, and skill level of installer. If a new greenhouse is proposed, an earth tube could be installed easily, as long as the soil beneath the site could be dug to a sufficient depth. The tubing is more unwieldy than pricey, but the main point of concern should be how large the diameter of the tube should be. The tube could be made of plastic, concrete, clay, or metal. In areas with high ambient humidity, mold in the tube may be a maintenance expense and health hazard for human and cultivar alike. A tube large enough for easy clean-out may be worth consideration, or using a pre-season fog of a chlorine solution (or similar sanitizer) to sanitize sufficiently for safe use.

Solar panels are expensive, and positioning of a photovoltaic array may not be convenient for some sites. Locations of solar panel arrays usually require aiming the collection surface to be pointed in a south-westerly direction. This fact alone may interfere with the placement that is best suited for the greenhouse itself. Solar panels are typically priced per watt, so a cost of $5,000 would be incurred for 1000-watts at $5 per watt. The cost to install a grid-tied photovoltaic system runs $7.50 to $10.00 per watt, including all wiring, inverter, panel mounts, solar panels, grid connection, and labor. A 4-kilowatt system would bring the cost up to $40,000.00. This expense could be lessened by starting at lower levels and adding onto the system as the greenhouse operation grows. While solar panel setups are expensive, their potential for long-term solutions for greenhouse environmental control should not be underestimated; with a 25-year warranty on panels, a significant expenditure now could easily pay off future dividends. There is no reason to use solar panels if the greenhouse operator can comfortably afford grid-based power for the installed system controls. The only caution here is that electrical utility companies will surely raise the price per watt for delivery of power, making the solar panel system more valuable for future considerations.

Water-to-air heat exchangers can easily be built from components from other industries, or purchased directly from suppliers. The use of automotive radiators was a purely economic choice, since the author has significant sources available within that industry. Enormous heat exchangers can be found on popular online auction websites, so fitting the heat exchanger(s) to the specific needs of the greenhouse will likely be a financial choice. Most greenhouses have water running either inside or nearby that could be utilized for the water-to-air heat exchanger. The heat exchanger would increase the outgoing water temperature making it more comfortable for human use or as irrigation water. The outgoing water from the water-to-air heat exchanger could also be run through tubing beneath the plants to allow some additional heat to them. This aforementioned heat gain, resulting in warmer water at hose-end, would be reversed for winter heating, and would increase the risk of cold damage to humans or plant materials. Once heat has either been taken away or given to the transferable solution within the water-to-air heat exchanger, the uses for super-heated or super-cooled solution is up to the imagination of the user. Oil-fired heating systems could get a significant boost of intake air temperature by using water-to-air heat exchangers. The increased temperature of incoming air would directly affect the amount of energy needed to heat the outgoing air for greenhouse heating.

The estimated cost to install this type of system into a 30' x 90' greenhouse could fall in the range of $13,000 - $15,000 (see Appendix, Table 1). Some cities offer photovoltaic (solar) system rebates for businesses, and Federal tax credits are also available. Although this is not an inexpensive option for some growers, it could be an investment for a long-term benefit to be sure. The larger system would require at least six water-to-air heat exchangers, 2000+ watts of solar panel power, and two 200mm (8 inch) earth tubes than in the smaller greenhouse. Most of the other components would remain functional in the larger area. Installation positions would need to be adjusted for the larger area; the heat exchangers could be configured with three on each side of the house aimed longitudinally with fans mounted to create a circular airflow.

Conclusions

Greenhouse growers worldwide spend part of their potential income warming and cooling greenhouses. The proposed project could alleviate, possibly eliminate, the expenses of massive oil-fired heaters or evaporative cooling systems. While this combined system does help to control greenhouse environmental conditions, it may serve a purpose as a pre-conditioner for typical control systems. By using natural heat exchange methods, the conditions within a greenhouse may be moderated. The temperature drop of 7.8°C (46°F) described above could make a functional summertime greenhouse a possibility: seedlings could be grown on 37.8°C (100°F) and warmer days in a greenhouse area that is being cooled to 27.8°C (82°F). Further cooling would be achieved using this system in conjunction with shade cloth or whitewash, two commonly-used cooling methods. This could expand the growing season, allowing the early adopters to get products ahead of the competition and gain a larger market share for their agricultural effort. Another method of temperature control using the above-stated method could be considered using a closed-loop pump system with the piping buried a few feet below grade and filled with an anti-freeze solution. The anti-freeze solution could be pumped through the heat exchanger and returned underground to transfer accumulated heat into the surrounding soil. A wet plate heat exchanger simulation conducted by DeJong and VanDeBraak (1993) appears to be promising for future projects, but the system may harbor significant expense for the adopter.

Development and Implementation of Project

- January 2011 - Trenched 80 feet long x 8 feet deep for earth tube. Installed earth tube with several inches of gravel beneath and over conduit for increased heat transfer.
- February 2011 - Constructed greenhouse over tube ends. Installed electrical system (solar panels, batteries, wiring, tube fans, and other electrical components). Test-ran all circuits. Found that the system could not be run with a 12-volt only system due to solar panel design. Converted electrical system to 24-volt due to solar output. Since Winland EA400 is 12-volt design, a 24-volt-to-12-volt converter was required.
- March 2011 – Assembled heat exchanger system. Installed three radiators and plumbed with one-inch PVC piping for water flow. Insulated heat exchanger box for protection from freezing and excessively-warm temperatures. Installed heat exchanger into greenhouse and connected to solar-powered shallow well pump.
- April through November 2011 – Collected data from loggers, made changes to design to optimize system function, and began formal comparison of greenhouses as of July 1, 2011.
- November 2011 – System is very reliable with no malfunctions and can be run for day-to-day operations without user involvement.

Appendix

Project Expenses (Estimated)

Components	Cost	Supplier	Specifications
Polyethylene Tubing	$135.00	Tractor Supply Co.	
4 X 12/24v Axial Fan @ $17.00	$68.00	www.surplus center.com	283 cfm / 26watt / 1.1amps
Winland EA400	$250.00	www.ebay.com	4 Zone 12Volt
4 X Winland TEMP-L-W Sensor @ $70.00	$280.00	Local Alarm Supplier	-58 to 158°F
Water to Air Heat Exchanger	$275.00	www.ebay.com	24 X 24
2 X Data Logger @ $50.00	$100.00	www.ebay.com	
Xantrex Solar Charge Controller	$190.00	www.ebay.com	C 60 (60 amp)
Pyle 24V - 12V Converter	$70.00	www.amazon.com	
4 X AGM Battery @ $295.00	$1,180.00	Battery Supplier	105 Amp Hour
2 X 150 Watt Solar Panel @ $3.00 per watt	$900.00	Solar Provider	24 Volt
3 X Bosch Single Pole Relay @ $15.00	$45.00	Auto Parts Supplier	30 amp
Fuse Box	$50.00	West Marine	
Plywood	$15.00	Home Depot	1/2"
3 X Radiator @ $50.00	$150.00	Auto Parts Supplier	Volvo 850 Radiators - Used
Misc. Wiring / Conduit / Valves	$200.00	Hardware Store	
Total	**$3,908.00**		
Items in RED were donated for this project.		Costs are estimates for purchase.	

Table 1

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