Development of a Solar Thermal Water Management System (STWMS) – An Undergraduate Research Experience

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Abstract

To reduce the negative impact of energy usage on the environment and reduce the cost of using fossil fuel, people must be encouraged to use the available sources of renewable energies in particular solar energy. Utilizing of solar energy requires solar collectors. The two types of solar collectors available are: non-concentrating or flat plate type, and concentrating or focusing type solar collector. In the non-concentrating type, the collector area that intercepts the solar radiation is the same as the absorber area. While in concentrating collectors, the area intercepting the solar radiation is much greater than the absorber area. The concentrating collectors are more efficient than the non-concentrating and can provide higher temperatures. The main objective of this senior project was to develop solutions to harness the solar energy and use it to develop an efficient residential Solar Thermal Water Management System (STWMS). We believe that this system will make life easier for mankind and save our environment.

Introduction

The development of the Solar Thermal Water Management System (STWMS) has been highly influenced by the current direction of the country, which is to advance energy conservation through renewable energy opportunities. Residential applications of the solar water heaters have the potential to replace expensive electrical and gas water heaters that prove to be costly to operate. Universities, especially engineering education departments, are incorporating initiatives to back the government in their strategic plan of energy independence by motivating students to use their engineering knowledge to formulate ideas and machinery that can be used to excel the

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productivity of the proposed proposition. In engineering education, the use of high tech equipment is the most beneficial feature to formulate concepts for new innovations. Students engage in process modeling, testing and simulation, imitates data acquisition and process control. Virtual applications enhance both theoretical and hands-on knowledge of engineering technology students by supporting laboratory experiences. There has been an immense amount of research and development on behalf of the Engineering Technology seniors at TTU for the simulation of the STWMS. The main goal of the project was to construct an energy independent system capable of continually replenishing itself by creating a solar collector box that is cost effective, efficient and environmental friendly. The design focuses on the need for use of renewable resources and the need to reduce electricity costs in TN households. The design promotes the use of solar water heating systems in homes. The project is also used to promote the use of green development and solar technology.

Approach

Brainstorming was conducted and ideas were shared amongst team members and project advisor to make the best configuration for the system. The project helped build on an already well-rounded education, by enabling each team member to learn how to execute an in-depth research analysis and acquire project management skills, by starting with a conceptual idea and finding factual information and resources to make the ideas a reality. The project also helped emphasis the fundamental importance of team work, because each team member was able to learn new things from one another, which made the project have a practical engineering atmosphere.

This paper is divided into six sections. In the first section, the benefit for using the SWTMS is analyzed with measurable outcomes of gain. The second section looks at the energy transfer principles and how they can be used for Solar Thermal Systems. The third section demonstrates how the composition of the system, along with functionalities of its operations. The fourth section involves details regarding the control system of the STWMS, which explains how the system is linked together. The fifth section shows the output of the system by comparing the STWMS with today's standard water heater and by comparing there correlated energy efficiency data. The final section involves prototyping of the STWMS through manufacturing and system assembly/integration to bring ideas into reality for feasible measures to the cost of production.

Benefit of the Study

Renewable energy alternatives have multiple benefits for their users; the STWMS have three main benefits that include environmental gains, economical profit, and energy production. The system would benefit the environment simply because it does not run completely on electricity or any other type of fuels; therefore it does not emit any harmful byproducts. The STWMS system is basically pollutant free. In the long run, the system would help reduce the amount of pollutants released into the air, which would not only benefit the environment but it would help improve the health of humans due to the fact that we would be breathing in cleaner air. The economic benefits of the system would not necessarily be evident at first. The consumer would have to spend initial investment costs upfront to purchase the STWMS, but in the end, that consumer would receive a payback through the money they saved on their monthly utility bill. The amount of money saved would correlate to how efficiently the system works, and that basically depends on what region of the country the consumer lives in and how much sunlight that region receives.

Lastly, the STWMS would benefit the energy production of any household or business that utilizes it. A more realistic indicator of the performance of the solar thermal water heater would be its daily energy output from its collectors system. Based on a typical solar thermal water heater, the output contributes typically 7-10 kilowatt hours per day, depending on the solar resources and the type of collectors being used. Whereas a typical residential electric water heating system consumes about 12-14 kilowatt hours per day, depending on the temperature of the groundwater that enters the system. As you can see, there are multiple benefits of the solar thermal water management system. The abundance of savings are reason enough for consumers to want to purchase and install the system into their existing water heating system for significant cost reductions.

Energy Transfer Study

The three main basics of heat transfer are Conduction, Convection, and/or Radiation. Conduction is the transfer of thermal energy from one object to the other through the direct contact of each other where the heat moves from the hotter object to the colder object. In this transfer the amount of heat transferred is proportional to the area of contact and the temperature difference. Convection is the heat transfer from one place to another by the movement of fluids. The amount of heat transferred by convection is affected by the area of contact, the temperature difference, and the amount of constraint on the movement of the fluid such as the viscosity of the fluid. Radiation heat transfer of heat energy is by electromagnetic radiation. Radiation operates independently of the medium through which it occurs and depends upon the relative temperatures, geometric arrangements, and surface structure of the materials that are emitting or absorbing heat.

Solar Radiation at the Earth's Surface

Solar radiation is energy emitted by the sun reaching the Earth's surface, which can't be turned on or off (Figure 1). To understand this theory of solar energy system, we should find how much energy is available from the sun, and how this amount of energy is divided among day and year. Accordingly, the average solar radiation produces 1.35 kWh of energy per square meter of surface, which is directly facing the sun above the earth's atmosphere. Radiation travels directly from the sun to Earth without being scattered or diffuse then radiation has been scattered as it travel through the atmosphere. The effect radiation causes on the Earth's atmosphere is the inability for meteorologist to predict the amount of radiation that will reach the Earth's surface, due to radiation being scattered and absorbed by air, water evaporation, dust, smoke, and smog.

The sun moves from east to west through the sky throughout the day, but moves on a different path as the Earth's tilt changes relative to the position of the sun throughout the year. The declination is the angular position of the sun at solar noon with respect to the plane of the equator, which is demonstrated by Cooper's equation:

$$\delta = 23.45° \sin\left(2\pi \frac{284+n}{365}\right) = 23.45° \sin\left(2\pi \frac{284+122}{365}\right) = 15.21°$$

Where, $n =$ *days = 122 (2nd MAY 2014),* δ = Declination

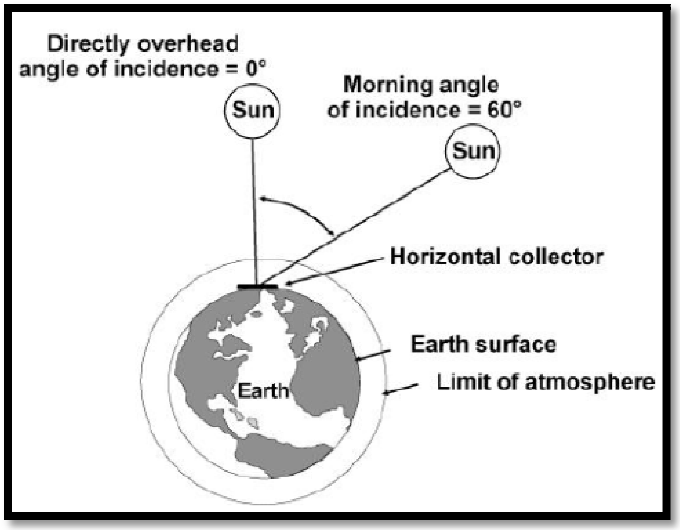

Figure 1: Solar Radiation Emitted to the Earth's Surface

The solar hour angle [13] is one of the most important factors involving heat energy (Figure 2). When the solar angle decline or inclines, it fluctuates the thermal energy of the sun's radiation. At solar noon the hour angle is 0.000 degrees, with the time before solar noon expressed as negative degrees, and the local time after solar noon expressed as positive degrees. For example, the hour angle when the sun rises in the morning in Cookeville, Tennessee is -100.24° *(2nd MAY 2014),* from the hour angles equation:

Cos ω_s = -tan ($\boldsymbol{\psi}$)$*$ tan (δ)

Where: $\omega_{s\,=}$ $hour\ angle$

$\boldsymbol{\Psi}$= latitude,

δ= Declination.

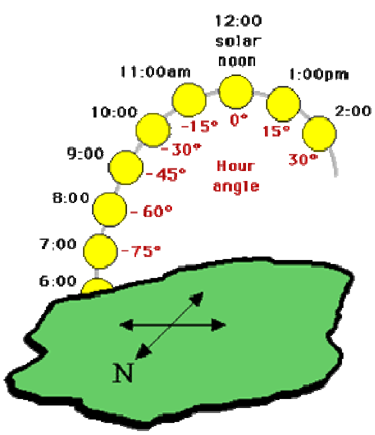

Figure 2: The Solar Hour Angle [13]

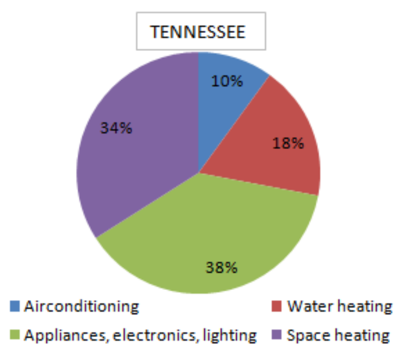

Figure 3: Average Household Energy Use in Tennessee [12]

The angle closest to 0° will attain more sun radiation and the angle further from 0° will have a reduced amount of sun radiation correlated to the origin of the surface of the solar collector.

Therefore, the best collector tilt depends on the particular application where sun is required throughout the year.

The end product has the potential to become the most economical and efficient system to be used in households due to the application of convection and radiation within the collector box, and convection application within the storage tank where the fluids act as a heat exchanger. In addition, the product has potential to reduce household energy consumption in states such as Tennessee.

Household Energy Use in Tennessee

Average electricity consumption for Tennessee households is 33% higher than the national average and among the highest in the nation (Figure 3) [12]. The electric water heater consumes about 18% of the total household energy. Compared to other areas of the United States, the warmer weather in Tennessee and its neighboring states means that air conditioning accounts for a greater portion of home energy use (10%), while space heating accounts for a smaller portion (34%).

STWMS System Description

Figure 4 shows the schematic CAD drawing for the system assembly. The STWMS is a hybrid solar water heating system. Like the name implies, combine two or more heat sources: electrical heat generation together with solar preheating of the incoming city water. The hybrid system under consideration will provide a high level of energy saving. The improved functionality allows the system to have automated features to run fully of solar energy during moderately hot days of the year, and during mild weather the system has a joint operation of solar and electrical powering to generate hot water. The significance of this configuration results as an effective method of creating a way to utilize renewable energy, because the sun is the most powerful resource known to mankind.

The first component of the STWMS hybrid system involves the solar aspect of powering the system. In order to generate and retain the power from the sun, sun radiation is extracted from the sun and stored to fervor the water. The design of our solar collector box for absorbing incident solar radiation was selected by combining two of the four solar collector boxes commonly used in the industry. The integration of the flat-plate collector and the parabolic trough provides benefits from both concepts. The flat-plate collector theme allows heat radiation to be collected and entrapped in the parameter of the box dimensions, in order to preserve heat collected.

Solar radiation is captured in the collector box and focused at any point along parabolic curves where it is then reflected towards the copper pipes which contain propylene glycol. Glycol is used to store the sun radiation then used to preheat water. After being heated, glycol is sent to a storage tank where it acts as a heat exchanger. An additional copper pipe is connected to the tap water outlet, which passes through the glycol tank where the water is heated and sent to the water heater storage tank similar to the conventional heating system.

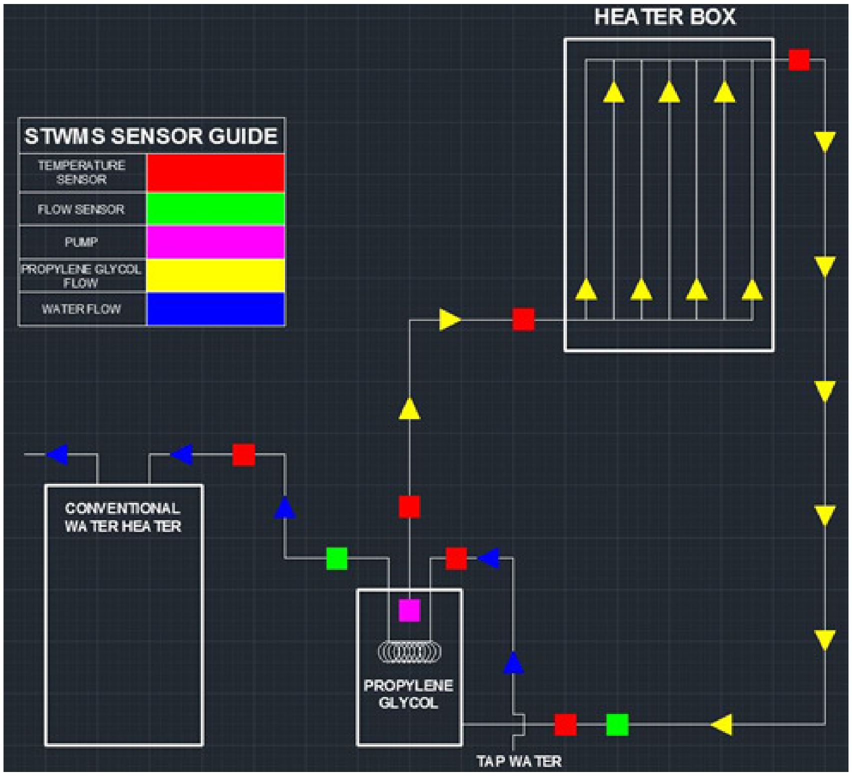

Figure 5: STWMS Plumbing/Electrical schematic

The second component of the STWMS hybrid system involves an alternate power input to the system through electric power supply. This aspect of the system is automated, by converting power between solar or electrical power. The functionality of the automated system is based on a thermostat reading that are interconnected to a control system that reads the weather conditions for operations. The electrical power can be provided by local utility companies, then connected to the STWMS for power supply alternatives to heat water.

Raspberry Pi Data Microcontroller/Data Acquisition

The interface to the STWMS involves a Raspberry Pi micro-processor (Figure 5). Raspberry Pi is used to connect all the temperature sensors for data acquisition and control. The Raspberry Pi is a low cost, credit-card sized computer that plugs into a computer monitor or TV, and uses a standard keyboard and mouse. A simple python code is used to configure temperature sensors. The Raspberry is responsible for automatically collecting liquid flow and temperature data. The processor also has capabilities to turn glycol pump on and off depending on weather conditions, and day versus night.

If the glycol is flowing through the collector box, the system collects data and writes it to the file. If glycol is not flowing through the system, the program writes a zero indicating that there is no flow. The same applies to the flow of water through the system. The system behavior contains processes that transform inputs into outputs (material, energy or data). Data collection is stored into excel spreadsheets for analytical analysis of hot water produced, solar input, and the time of

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regulation hybrid durations. A flow meter is also incorporated into the Raspberry Pi controller, with temperature gauge readings to measure how hot the water becomes.

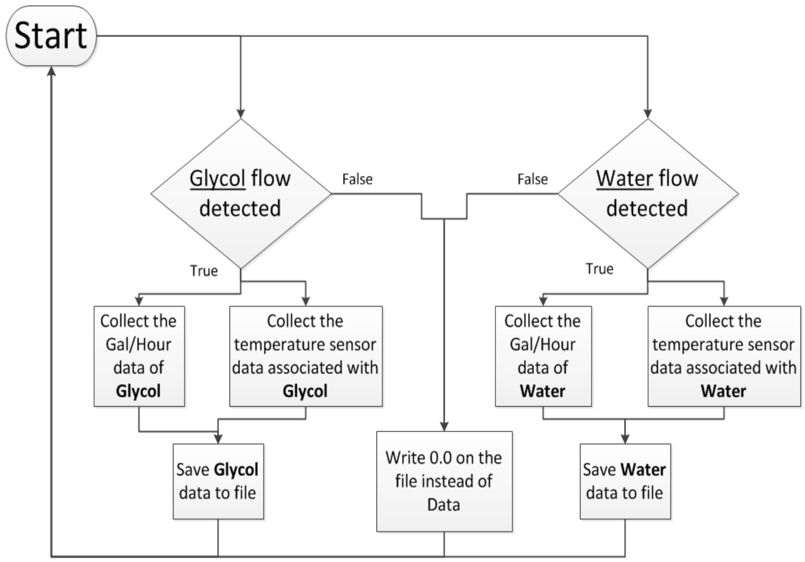

Figure 5: Raspberry Pi Programming flowchart

STWMS Output Study

To measure heat energy the standard metric unit is Joules (J). The formula to obtain energy transfer is: $\Delta Q = M \times C_p \times \Delta T$, where Q is the quantity of energy transfer, M is equal to the mass of substance in kg, C_p (kJ/kg°C) is the specific heat capacity of the substance, and ΔT (°C) is the amount of temperature difference in the substance.

Since this system is indirect system the lowest temperature would be the minimum room temperature of 63°F (~17^{o}C), and our target temperature is 125°F (63^{o}C). The one liter of water is 1 kg and the specific heat of water (Cp) is 4.19 J/kg ^{o}C. So the energy needed to raise the temperature of one gallon of water (3.78 kg) from 63^{o}C to 17^{o}C (ΔT = 46^{o}C) is equal ~720 kJ**.**

Since the required energy and efficiency have various factors to be considered, another similar formula is used in order to make comparisons. Energy (E) required to raise temperature of 1 liter by 1°C is 4.19 kJ. If assuming capacity of the system is C liter and temperature of water is raised by T °C, the energy required should be: $E = (4.189 \times C \times \Delta T)$ kJ. Using the same assumptions:

$$E = 4.19 \text{ kJ/kg } ^oC \times 75 \text{ kg} \times (125\ °C - 63°C)5s \text{ kJ} = 97{,}417.5 \text{ kJ}$$

We also made assumptions for the determination of the solar collector area and angle of inclination:

[1] Heat required per day = 97,417.5 kJ

[2] Solar energy radiation on the inclined surface of the collector is:

$(619 \times 9 \times 60 \times 60)$ kJ/m^2/day = 20,055 kJ/m^2/day

[3] The collector box efficiency at minimum is considered 40%

[4] Collector box area = (Energy required/ Energy available x efficiency)

$(97,417.5 / 20,055 \times 0.4)\ m^2$

[5] Slope of collector β and angle of inclination δ is calculated from equation:

$\delta = 23.45 \sin [0.9863(284 + n)]$

For May, n = 15

$\delta = -21.27$

Slope of the collector box β is calculated by:

$\beta = (Q - \beta)$, where Q is latitude at test site = 36°, 9N

$\beta = [36.9 - (-21.27)] = 58.17°$

This shows that the collector ideally should face south at an angle of ~58°C (Figure 6)

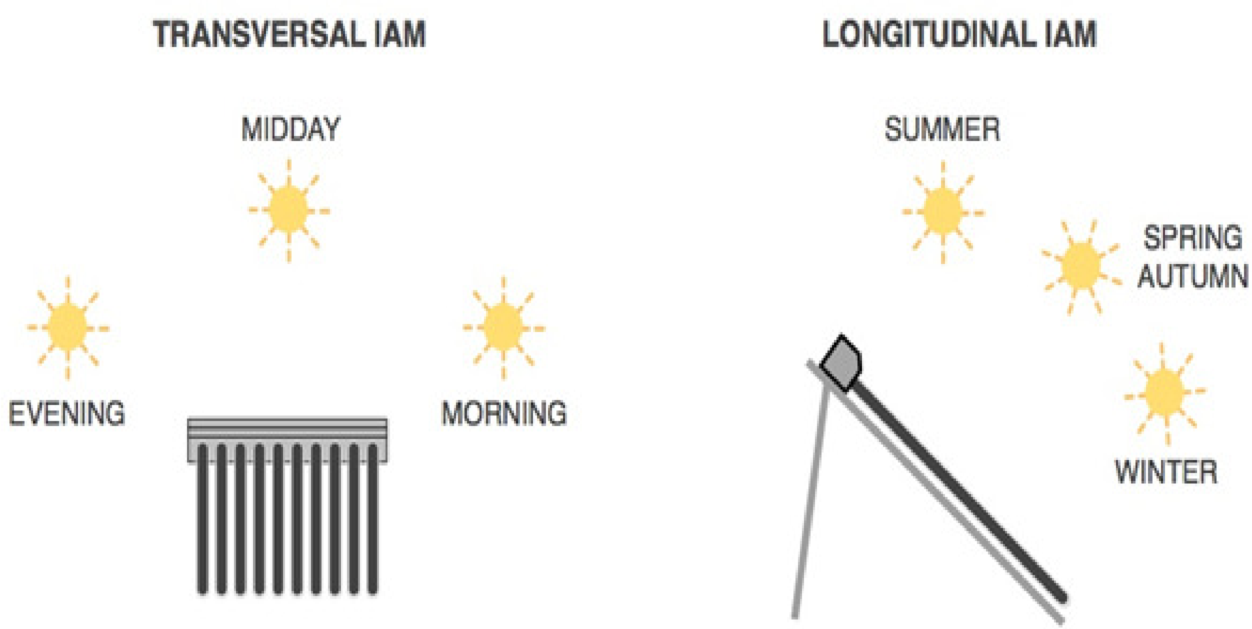

Figure 6: Slope and Direction of the Sun Collector

The angle of the collector in relation to the sun is crucial to maximizing efficiency of the solar collector box. The output from the solar collector box changes as the angle between the collector box changes in addition to the more surface area and absorber copper pipes absorber.

Solar Collector Fabrication

The steps used for building the solar collector are shown in Figure 7:

- **Frame:** A 4'x6' base of collector box frame was made from plywood and reinforced by pieces of 2'x8' treated pine wood to create our side walls for the frame.

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- **Insulation/support/water seal:** Styrofoam was placed inside the collector box by lining all the sides and the base of the frame with the installation material, in order to secure no thermal heat inside the box.
- **Parabolic trough and reflective materials:** We then split PVC piping in half and used seven of the cut outs, and placed them in a linear array inside the collector box, in order to create a parabolic layout. Then lined the PVC piping with Mylar material, to create a reflective surface, by measuring and tailoring the Mylar to the contours of the PVC piping. Then we used an adhesive spray so that the Mylar could bond to the PVC piping.

Figure 7: Steps used to fabricate the Solar Collector

- **Pipe supports:** the CNC machine used to cut out positioning supports, which will be responsible for placing our copper piping at the center of the parabolic focal point.
- **Copper assembly:** Our next step involved soldering copper coils into copper pipes, which will be used to bring water into the system and distribute it out for storage or usage. Finally, we placed our copper assembly into the pipe supports slits, and position the copper runner bars inside the inlet and outlet cut outs.
- **Acrylic casing/glass support:** We covered the solar collector box with a single glaze acrylic to insulate the pipes from the outside environment. We installed a rubber weather seal around the perimeter of the box to further insulate the box.
- **Thermal paint:** the last step step involved coating the frame of the collector box with high heat thermal spray paint, in order to attract more heat to the structure and absorb it into the system. The thermal paint will help in maximizing heat through radiation entrapment and containment.

Installation of the Solar Collector Box

The solar collector array is set at a 40° angle on the top of the lab inclined roof facing south, in order for the parabolic surface to have maximum exposure to direct sunlight. The box is stationary without any permanent connection to the roof due to the high coefficient of friction between the rubber roof and wooden support brackets at the base of the structure. As shown in Figure 8, the inlet and outlet pipes allow glycol to be circulated in a continuous loop, so that the ground water can be pre-heated before being stored into the conventional water heater for use.

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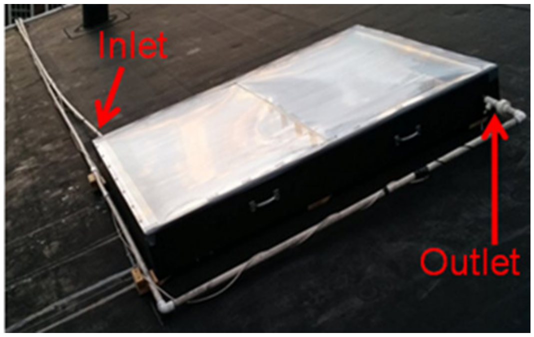

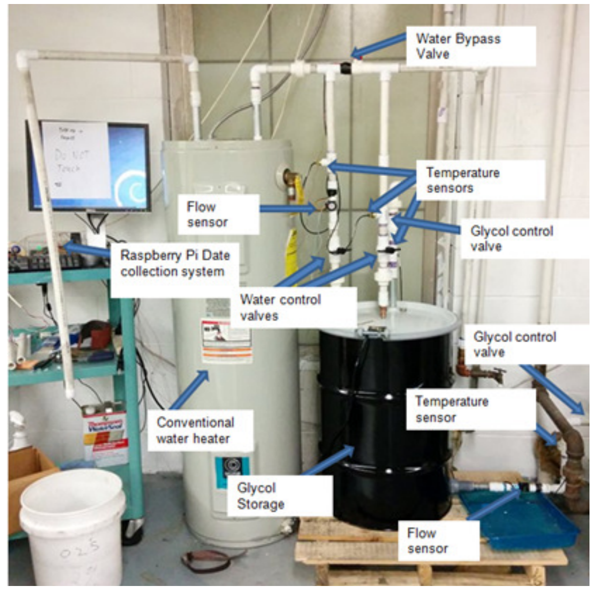

Figure 8: The Solar Collector Box Mounted on the Roof of the laboratory

Figure 9: The Assembled STWMS installed inside the Laboratory

Complete STWMS Assembly

Figure 9 shows the STWMS assembled system. The figure shows the 30 gallons electric water heater and glycol storage black drum which constantly circulates thru the sun collector box on top of the building to be heated and stored in the drum with a heat exchanger for preheating water before it goes to the electric water heating system. The system uses sump pump to circulate the glycol solution within the solar collector and storage drum. Flow sensors and temperature sensors are installed on the city water and the glycol valves inlet and outlets. Also, the Raspberry Pi Data collection is shown in the figure to which all the sensors are connected for data acquisition/control the system.

Preliminary Test Results

Figures 9 and 10 shows preliminary data collected from the solar water heater in the month of April 2014. Several system improvements happened since to maintain the temperature inside the box in the winter time. The improvement included using double glazed covers and using vacuum tube solar collector.

The system was able to heat 10 gallons of water from an initial temperature of 94ºF to a final of 106ºF before more water was added in the glycol storage drum and before adverse weather conditions caused temperature dropped. Overall, the system performance meets the desired expectations. However, more testing is required during clear weather.

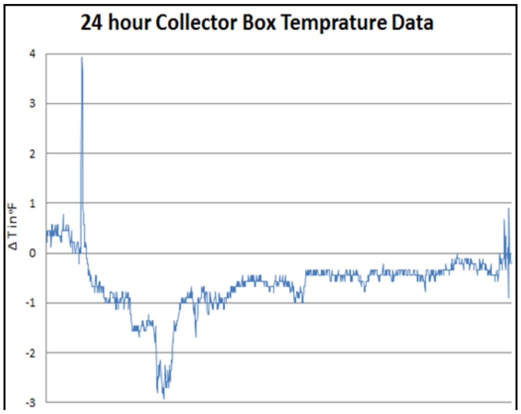

Figure 9: 24 hour Solar Collector Box Temperature Data

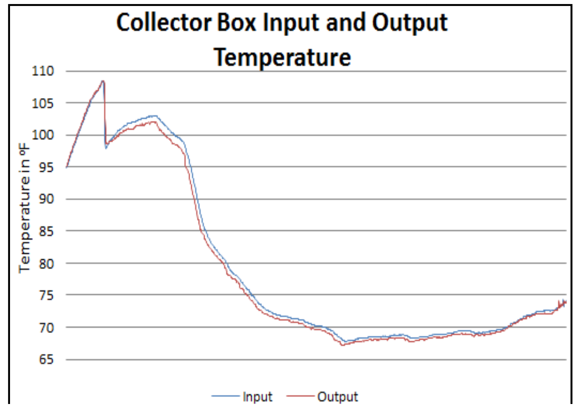

Figure 10: Solar Collector Box Input and Output Temperatures

Conclusions and Lessons Learned

The proposal for designing this project revolved around alternative solutions for improving the current household electrical water heater energy efficiency. Our senior project's team found that using the solar energy would be the best solution for this problem. Simply because the energy from the sun is free once you pay for the initial cost of a Solar Thermal Water Management System (STWMS). The anticipated payback for the STWMS is ~7 years in the Tennessee region while saving the negative impact on the environment and reduce the U.S. dependency of foreign oil. The simple payback will become more expedient in the warmer climate states like Florida and South Carolina where the payback period would be 2-3 years. During the period of this study our research team was able to: 1) learn about solar energy and how it is used in the world today, 2) learn some new skills in manufacturing processes like welding and plasma cutting, 3) explore new ideas and concepts to produce the final product, 4) learn more about product design from concepts to development, 5) use critical thinking skills to find solutions for technical problems, and 6) use the learned project management and team work skills to overcome problems we faced during this process and meeting project's deadlines.

Acknowledgements

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Biographies

Nathan Frazier was born and raised in Knoxville TN. He currently works for UPS at one of their store locations. He received his Associates of Science with a Concentration in Engineering from Roane State Community College in 2012. He earned his Bachelors in Engineering Technology with minor in Business from Tennessee Technological University in 2014. He was the Manufacturing Lead for the Formula SAE team in 2013. He is currently trying to get selected for the Officer Candidate School for the Marine Corps. Upon completing that course, he wants to become a Logistics Officer.

Kendal Lewis is an African American native of Chattanooga, TN. He received his Bachelor degree in Engineering Technology in May 2014. He is currently employed as a Quality Engineer at Aisin Automotive Casting in Clinton, TN. He was able to gain on the job training by working as an intern for Honda Manufacturing Alabama, amidst his college studies. His career goals are to lead the engineering industry with skill, integrity, and responsibility. His collegiate experience was filled with many faucets of interest, including involvement in multiple engineering clubs, the engineering joint council, and the study abroad program. He also participated in undergraduate research, minority affairs, received a host of academic awards, and worked in a joint grant between the Society of Manufacturing Engineers and the U.S. Department of Energy, conducting industrial energy assessments.

Steve Ngwira was born in Malawi and he received his bachelor degree in Engineering Technology with minor in Business in May 2014 as an international student, He was awarded numerous scholarships for academic excellence, research and leadership roles Currently, Steve is a Process Engineer at Nissan in Canton, MS. He focuses at improving supplier manufacturing processes and reducing Total Delivered Cost (TdC). Prior to joining Nissan he worked with CEVA as a logistics specialist. While he was at TTU, he worked for 2 years as an intern at Bosch in Safety and Logistics Engineering.

Priyam Patel is a Manufacturing Engineer at Akebono Brake Corporation since July 2014. He graduated from Tennessee Technological University May 2014 with a Bachelor of Science in Engineering Technologies and minor in Business. He is a Fanuc Trained Robot programmer with the Handling Tools Operation. Before joining Tennessee Technological University, Priyam graduated with honors from the Lebanon High School located, Lebanon, TN. He finished his elementary and middle schools in the city of Ahmedabad, Gujarat, India. Priyam was born in India and he speaks 3 languages, including Gujarati which is his native language, Hindi which is the national language used by the Republic of India, and English.

Dr. Ahmed ElSawy joined Tennessee Technological University (TTU) as a Professor and Chairperson, Department of Manufacturing and Industrial Technology in July 1999. Prior joining TTU, he was a professor and graduate program coordinator in the Department of Industrial Technology at the University of Northern Iowa. Before that, Dr. Elsawy founded a Manufacturing Engineering Program at St. Cloud State University in Minnesota. He served as a full professor at the Department of Mechanical Design and Production in Cairo University till 2006. Dr. ElSawy teaching and research interests are in the areas of material processing, metallurgy, manufacturing systems, recycling and reuse of solid waste materials and renewable energy. Dr. ElSawy received ~ $2M of state, federal, and industrial grants in support of his laboratory development and research activities. He advised several masters and doctoral students who are holding academic and industrial positions in the USA, Germany and Taiwan. Dr. ElSawy has numerous publications in national and international conferences and refereed journals.