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تقييم فاعلية زيادة الأداء لأنابيب الطاقة الشمسية المجوفة

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الخـلاصــة

في عالم سريع النمو والتطور، فإن تأمين إمدادات الطاقة التي تعتمد عليها مجتمعاتنا أصبح أساسيا من أجل الاستمرار في النمو، وللحفاظ على الموارد الطبيعية من حولنا. تطوير الطاقة المتجددة، مثل تلك التي يتم الحصول عليها من الطاقة الشمسية، والتي يمكن أن تساعد في تزويد الناس بمصدر موثوق وآمن للطاقة في جميع أنحاء العالم. أنابيب الطاقة الشمسية المجوفة هي وسيلة نظيفة وآمنه واقتصادية وأكثر كفاءة في تسخين المياه، وكذلك فهي مصدر دائم ويمكن تنفيذها بنجاح في العديد من المناطق الجغرافية والمناخات المختلفة. إن الهدف من هذه الورقة هو تقييم التحسينات المضافة في كفاءة إنتاج الأنابيب الشمسية المجوفة من أجل تسخين المياه مع إضافة العاكسات الشمسية خلف الأنابيب في عدة ترتيبات هندسية مختلفة. إن استراتيجية البحث اعتمدت على تحليل عدة متغيرات يمكن قياسها من خلال إجراء اختبارات من أجل قياس وتحديد الأداء الحراري لكل اختبار. ولهذا تم بناء جهاز، وتم اختبار أربعة أشكال مختلفة على مسافات متفاوتة: خلفية مسطحة، وخلفية 45o V-shaped وخلفية 60o V-shaped ، وخلفية نصف دائرة. بعد إجراء الاختبارات، وتحليل البيانات التي تم جمعها وكذلك الإيجابيات والسلبيات من كل تكوين وجد زيادة في كمية الطاقة الممتصة بواسطة الأنابيب الشمسية في جميع الحالات التي تم فيها وضع عاكسات للأشعة الشمسية. وعلاوة على ذلك، أظهرت نتائج الاختبارات زيادة في كل من الكفاءة وكمية من الحرارة المتولدة. وأخيرا فإن الأنابيب على شكل 60o V وعلى بعد 15.25 توفير بشكل كبير استهلاك الطاقة الكهربائية، ولذلك خلصت هذه الدراسة إلى أن التكوين على شكل 60o V هو الأكثر فائدة وإنتاجيه.

Evacuated Solar Tube Performance Enhancement Evaluation

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ABSTRACT

In our fast-growing and expanding world, securing a reliable energy supply to power our societies has become essential in order to continue forward as well as preserve the natural resources around us. Developing renewable energy, such as that acquired from solar collectors, can help provide people with reliable and safe source of power worldwide. Evacuated solar tubes are a clean, economical, and efficient method of heating water. They are robust and durable in their construction and therefore are able to be successfully implemented across many geographical regions and various climates. The goal of this paper is the evaluation of enhancements made towards the output efficiency of evacuated solar tubes for water heating with the addition of solar reflectors behind the tubes in various geometric arrangements. The strategy implemented was to analyze several measurable variables through each test configuration conducted in order to determine the thermal performance of the each test. Thus an apparatus was constructed, and four different configurations were tested at varying distances: Flat background, 45^{o} V-shaped background, 60^{o} V-shaped background, and a half circle background. After analyzing the data collected and determining the positives and negatives of each configuration, it was found that all cases where reflectors were implemented led to increases for energy absorbed by the solar tubes. Furthermore, all test configurations showed an increases in both the efficiency and amount of heat generated. The saving in power consumption for the 60°V-Shape tubes at 15.25 cm was significant, therefore; it was concluded that the -shape configuration is the most beneficial.

Keywords: Evacuated solar tubes; heat reflectors; solar azimuth; solar energy.

INTRODUCTION

Climate change, pollution, and energy insecurity have become major concerns for many societies as they correlate with the most basic and essential needs of humans (Stern, 2006). Renewable energy is essential to secure energy supply and replace fossil fuels via the utilization of clean, climate-stabilizing, non-depletable resources (International Energy Agency, 2007). Solar energy, defined as radiated light generated from the sun, is the most abundant natural energy resource on earth. The sun radiates energy uniformly in all directions in the form of electromagnetic waves, causing approximately 173,000 terawatts of solar energy strike the earth continuously, and this equates to "more than 10,000 times the world's total energy use (Pierce, 2012). Solar energy is a clean, inexhaustible and abundant natural resource, but unfortunately these positive attributes are diminished in light diluted availability of retrievable energy due to intermittent, uncertain, and inconsistent accessibility hourly, daily, and seasonally (Mishra & Saikhedkar, 2014).

The two current primarily used types of liquid solar collectors in domestic heating and hot water production are flat plate collectors and evacuated tube collectors. Evacuated solar tubes (EST) consist of heat pipes, which heat up water or in some cases air inside vacuum sealed glass tubes (Zambolin & Del Col, 2010). EST collectors are understood to yield stronger and more reliable performance, when compared to flat-plate solar collectors, especially in high temperature operations (Morrison et al., 2003). As a result, EST are widely used for water and building heating due to their good thermal performance as well as suitability for easy installation and transportation. Furthermore, they require no electricity to run (i.e. are passive technologies by nature) and produce no pollution, making them ideal long term financial investments. The resulting energy cost savings not only benefit the installer, but also contribute to a healthier and more energy-conscious planet.

The EST design was produced and published in 1986 as a solar energy collector element at the University of Sydney in Rheem, Australia. It was designed to yield low overall heat loss, when operating at high temperatures (Mishra & Saikhedkar, 2014). EST's are comprised of strong double-layer borosilicate glass tubes with high chemical and thermal shock resistance. The inner tube carries a heat exchange fluid, while the outer glass tube encases the entire system. A solar selective surface coating is also applied in thermal contact with the outer surface of the inner tube. An evacuated space between the two tubes is created, as most of the air between the two layers of glass has been vacuumed out in order to provide insulation, yielding reduced convective losses (Collins et al., 1986). The inside glass is dyed with dark navy blue color in order to encourage the absorption of sunlight. Sometimes this darker inner surface is coated with a "solar selective coating such as Al-N/A or AlN/AlN-SS/Cu" which is excellent for solar radiation absorption for drawing in energy while producing minimal reflection (Mishra & Saikhedkar, 2014). Inside each of the solar tubes is a hollow copper rod that is filled with acetone. Acetone has a boiling point of 50.5°C at normal atmospheric pressure, along with its high heat capacity of 75 J/(mol K) (Haynes et al., 2014). A selected gas is admitted to the evacuated space in order to "degrade" the vacuum and limit the stagnation temperature of the collector element. This gas is elected based on its hydrophobic characteristics, in order to absorb onto the selective surface coating at temperatures that are less than the predetermined design temperature. This allows the system to desorb into the evacuated space at temperatures greater than the design temperature, but not absorb significantly onto the outer glass tube (Collins et al., 1986). Finally the open ends of the concentric tubes are fused together to enclose the system.

Though conventional flat plate solar collectors are more effective in consistently warmer and dryer climates (i.e. in high intensity solar radiation), their benefits are reduced when exposed to cold, cloudy and windy conditions. Therefore, in areas that experience four seasons, or a variety of adverse weather, evacuated solar tubes become the more ideal option due to their strong and robust design as well as their larger capacity to perform better during these poor conditions. (Arora et al., 2011)

There has been a steady increase in research and interest in the development of solar gathering technologies. More specifically, solar technology has been gaining more attention, as it relates directly to water heating, solar cooking, irrigation, cooling, space heating and more predominantly for the pure generation of electricity (solar photovoltaic). Furthermore, this acquired solar energy is low in cost, does not pollute and require low maintenance. Also solar plant installation is relatively easy and the energy conversion devices do not cause noise pollution (Mishra & Saikhedkar, 2014). In turn, solar, as well as other renewable energy gathering resources have been gaining support with larger organizations and companies, as they begin to adapt more responsible habits and installations of said technologies. According to a projection by the International Energy Agency (IEA), solar power generators may produce most of the world's electricity within the next 50 years, reducing harmful greenhouse gas emissions (Sills, 2011).

In order to evaluate evacuated solar tube technology, a detailed mathematical procedure was developed by Tang et al. (2009) to estimate the daily collectible radiation on a single tube of glass within an evacuated tube solar collector configuration. This model was based on solar geometry as well as the knowledge of two-dimensional radiation transfer. Results showed that the annual collectible radiation on a tube is affected by many factors such as collector type, central distance between tubes, size of solar tubes, tilt angles and use of diffuse flat reflector, which can significantly improve the energy collection of collectors in comparison with flat-plate collectors. This was largely in relation to the fact that solar acquisition is highly dependent upon the following parameters: atmospheric pressure, absorbing coating, materials, tilt angle, orientation (direction the equipment is facing), application of evacuated tube collector with solar water heating (ETCSWH), and finally the geographic location and its corresponding solar radiation potential (Mishra & Saikhedkar, 2014).

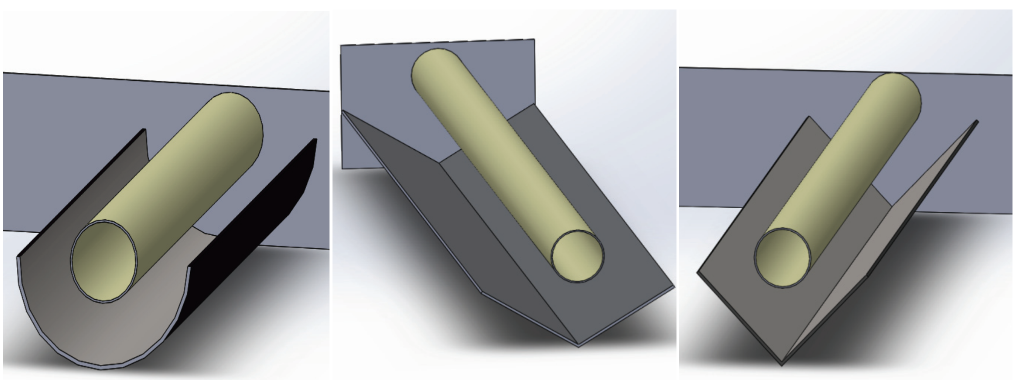
Another comparable study was conducted by Tang et al. (2011) to measure the effect of tilt angles for evacuated solar tubes. Two sets of water-in-glass evacuated tube solar water heater (SWH) were constructed and tested. Both SWHs were identical in all aspects, but had different collector tilt-angles from the horizon, with the one inclined at 22º and the other at 46º. Experimental results revealed that the collector tilt-angle of SWHs had significant influences on the daily collectible radiation and daily solar heat gain of a system, but insignificant on the heat removal from solar tubes to the water storage tank.

The primary source of CO_2 resulting from human activity is through the combustion of fossil fuels (coal, natural gas and oil) in exchange for energy. Currently the human population relies heavily on these resources, which provide sufficient electricity to power our world. The combustion of fossil fuels to generate electricity is the largest single source of CO_2 emissions, accounting for about 37% of total Unites states (U. S.) CO_2 emissions and 30% of total U.S. greenhouse gas emissions in 2014. It is because of this high cost to our environment that such support exists for the development of clean energy deriving technologies such as solar. Lower CO_2 emissions would help to improve air quality and yield a safer and cleaner environment, thereby reducing disease and health costs. Additionally, reduced fuel consumption decreases the fuel budget for people, companies and the government, allowing these funds to be spent elsewhere (Alkhaledi, 2015).

Traditional EST systems, where the designs do not integrate a back reflector are subject to loss of solar radiation absorption due to shadows and lack of sunlight exposure along the backboard facing half of the solar tubes. This research endeavor seeks to analyze the evacuated solar tubes technology with regard to the selection and analysis of an optimal reflector design to be recommended in future EST installations. Therefore, the goal of this study is to enhance the output efficiency of evacuated solar tubes for water heating, by adding high efficiency reflectors behind the tubes in an optimized geometric arrangement.

METHOD

Considering the many possible arrangements of reflectors for the solar tubes, it was decided to select a finite number that would give a range of performance over the reflector angle, which would then lead to optimum reflector position and yet give a manageable number for testing purposes. The process began with the designing of various reflector configurations. Five different configurations were to be evaluated and tested for this study: flat black material background (the control scenario), flat reflective background, two different V-shaped backings (45° and 60°) and a half-circle backing with reflective paper manufactured by 3M Corporation (see Figure 1), while the control side was designed with a flat wooden background.



(a) Half Circle (b) 60° V-Shape (c) 45° V-Shape

Fig. 1. Orientations of evacuated solar tubes evaluated

The distance between the EST center and the backing of the control side was kept constant, while the experimental side had two test distances; the first distance was 15.25 cm between the center of the solar tube and the backboard (see Figure 2), and the second distance was 10.20 cm from the center of the solar tubes to the backboard. The one exception was the half-circle, which had the tubes maintained at the focal point of the circle for all tests. Figure 3 shows a rendering of suggested system design containing 60° angled V- shape reflectors

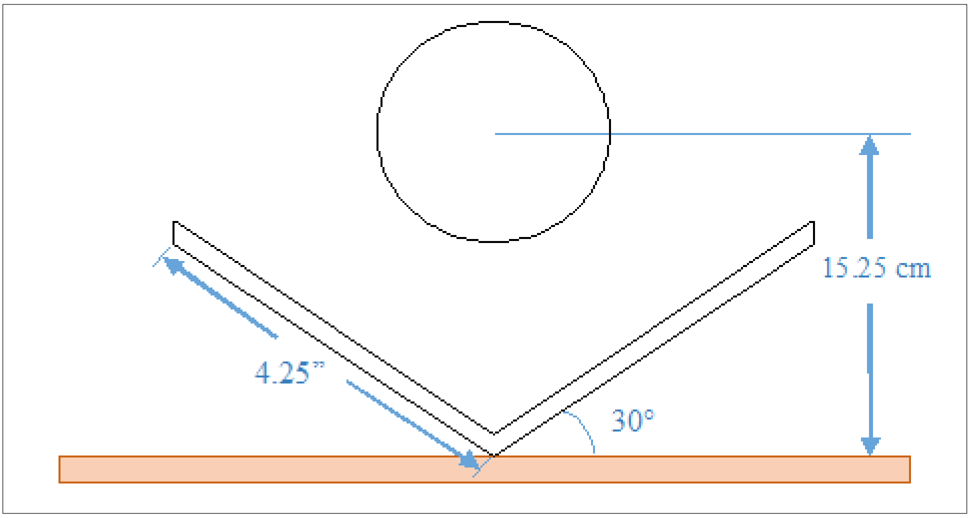


Fig. 2. Profile and dimensions of 60° design showing V-shaped reflectors and solar tube

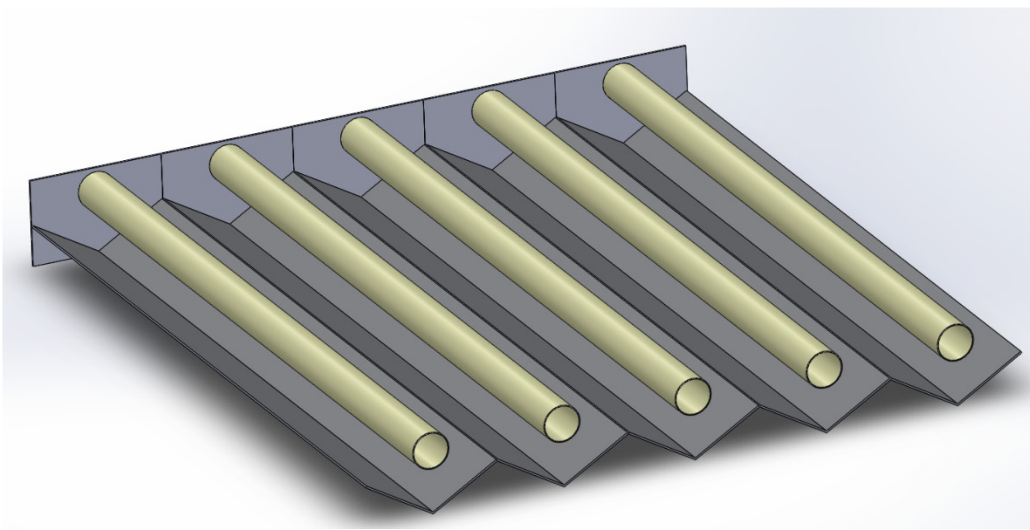


Fig. 3. Assembly of solar tubes with V-shaped 60° reflector backings

The strategy implemented was to analyze several variables that would be measurable through each test conducted, in order to determine the thermal performance of the test system that would be comparable across each test. In essence, this would allow for conclusions concerning the various orientations to be drawn. The notable variables evaluated for each test were: (1) inlet temperature of manifold, (2) outlet temperature of the manifold, (3) the mass flow rate through the tubes and (4) the reflector adjustment throughout the testing period. The tilt angle remained fixed at 60° and the collector faced south, as a constant component of this design.

The following assumptions were utilized throughout the completion of this experiment: heat transfer process was steady and conduction from walls of the glass tubes through the structure was negligible. The strategy implemented was to analyze several variables that would be measurable through each test conducted, in order to determine the thermal performance of each test.

The test apparatus consisting of two parts was completed where each part was comprised of three double-glass solar tubes (see Figure 4). The first part (on the left) would act as the control, while the second part would be considered as the experimental component. The tests for the two parts were conducted simultaneously, in order to minimize errors. Furthermore, several tests were performed during various weather conditions in order to consider a variety of climate influences. A total of 32 tests were conducted in Morgantown, WV, USA at 39.65° north latitude and 79.92° west longitude, between February and May 2015 with an average of 4.6 hours per test for a total of 192 hours of testing.

Several solar tubes were arranged in an array for each configuration with the tubes anchored at the top and bottom of the apparatus. These tubes were then directly fed into the designated manifold along the top. Inside each of the solar tubes was a hollow copper rod that was filled with acetone compound. Therefore, as heat was captured within the solar tube, it passed through the central copper rod and began to heat up the acetone. In turn, the acetone evaporates and rises to heat the top of the tube, where a bulb was located. This bulb was located within a copper jacket that was then placed within another horizontal copper pipe that spans across the length of the manifold (Ma et al., 2010). Water continually circulates throughout this horizontal pipe via the copper jackets that received heat from the solar tube's bulb, which then allowed for the collection of heat from the copper jackets (see Figure 5).

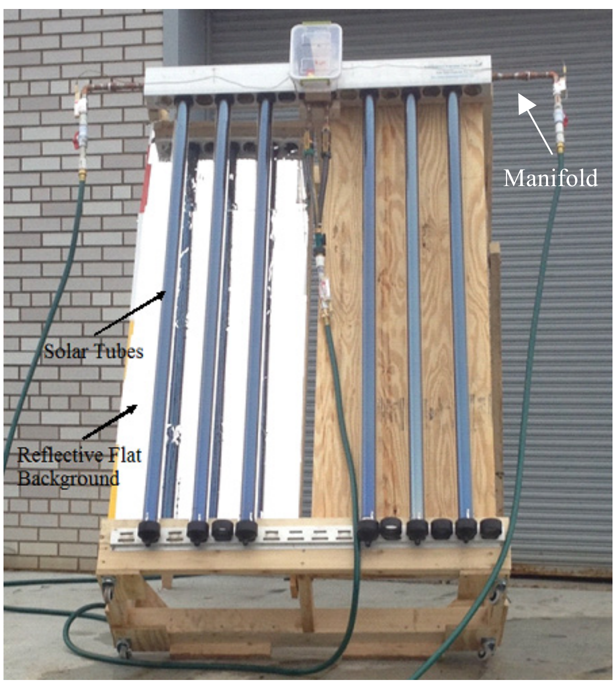


Fig. 4. Solar tubes test apparatus

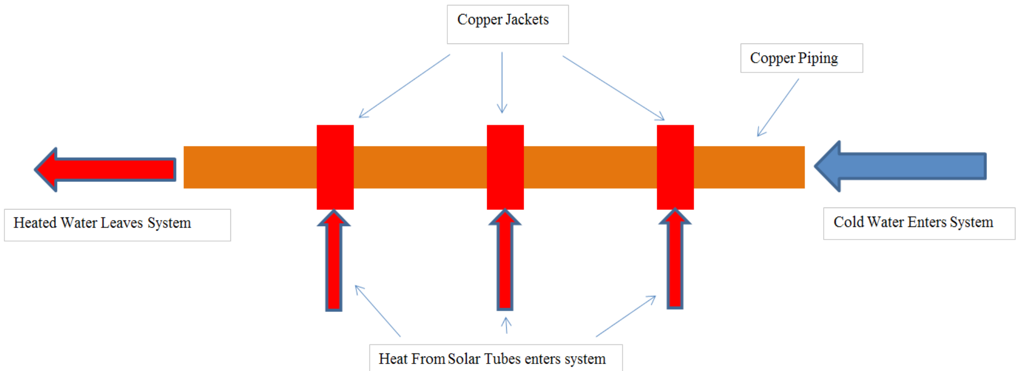


Fig. 5. Apparatus manifold front view

The water then continues to flow out of the pipe, over a thermocouple located just outside of the manifold on both sides. The thermocouple takes temperature readings of the water every 8 seconds. A third thermocouple was also utilized in order to document the temperature readings of the water, before it enters the manifolds to be heated. The data logger then records these three readings.

Three trials were conducted for each test configuration and angle. The increase in the amount of heat transferred from the control $(\dot{q}_c)$ to the water was calculated by averaging the three tests. The same was repeated to measure the heat transfer of the experimental side $(\dot{q}_e)$. After these two values were found, the difference in the amount of heat transferred between them was determined.

The mass flow rate was calculated by filling a bucket to a desired mass and dividing same by time. From these calculations the mass flow rate was determined to be 0.08757 Kg per second. Next, by using the known value for specific heat (Cp) of water as 4.1855 kg/ kJ*K, the total energy in watts derived for the solar tubes was calculated for each test using Equation (1) (Lienhard IV & Lienhard V, 2013).

$$\dot{q} = \dot{m} * Cp * (\Delta T) \tag{1}$$

Where:

is the energy collected [W/hr]

is the mass flow rate [kg/hr]

is the specific heat (established to be 1 kg/kJ*K for water)

is the change in temperature between the inlet and outlet [°K]

RESULTS

Results evaluated were the amount of energy collected $(\dot{q})$ (i.e. effective heat transfer), the efficiency of energy impacting the tubes versus the energy retrieved in the manifold, and the effects of the angle of incidence of the solar radiation. Each of the four different configurations has produced positive results. In order to select the most effective configuration, all resulting trends and data was considered.

Table 1 shows the average heat transfer of each reflector configuration and compares it to the control side, which has no form of reflector other than the wood it is mounted on and had been held constant throughout each test. The average heat transfer was calculated by taking the maximum value of heat transferred from both the control and experimental sides, and then calculating a percent increase from those two numbers. This test allows for investigation of the "potential" that a configuration has, as it can show the highest possible increase that can be generated.

Table 1. Heat transfer comparison between reflector designs

Reflector Configuration	Average Heat Transfer Increase v. Control (%)
Black Background @ 15.25 cm. from tubes	15%
Black Background @ 10.20 cm. from tubes	147%
Flat Reflective Background @ 15.25 cm. from tubes	83%
Flat Reflective Background @ 10.20 cm. from tubes	80%
45°V-Shape @ 15.25 cm. from tubes	137%
45°V-Shape @ 10.20 cm. from tubes	150%
60°V-Shape @ 15.25 cm. from Tubes	161%
60°V-Shape @ 10.20 cm. from Tubes	73%
Semicircle	96%

The following is a summary of the collected data and the various conditions for which the tests were conducted. The majority of tests lasted 5-6 hours beginning at 10 AM and ending at 4-5 PM. The solar azimuth varied during the tests, typically from 20° at the start to 70° later in the afternoon.

The first two test configurations were flat backing with black material placed on it. Tests were conducted on a same day at a distance of 15.25 cm between the center of the solar tube and the backboard. The average heat transfer increase was 15%. The second test was also conducted at 10.20 cm from the center of the solar tubes to the backboard, on a sunny day. Heat transfer improvement in the second test was much better at 147%.

The next sets of tests were conducted with a flat and reflective backing. A total of two tests were conducted. The first test was conducted at 15.25 cm on a sunny day. The average heat transfer increase was 83%. The second test was conducted at 10.20 cm from the center of the solar tubes, also on a sunny day. The heat transfer increase was 80%.

Two tests were conducted with 45º V-shaped reflective backing. The first test was conducted at 15.25 cm and the weather was sunny. The average heat transfer increase was 137%. The second test was conducted at 10.20 cm and showed very promising results. The weather was sunny for the duration of the test with a heat transfer increase of 150%.

Another two tests were conducted with 60º V-shaped reflective backing. The test was ran at a distance of 15.25 cm with sunlight for the entire duration of the test and in turn, results showed that the average heat transfer increase was 161%. While the second test was conducted at 10.20 cm from the center of the solar tubes and the heat transfer increase was 73%.

The final set of tests was done with 15.25 cm diameter, half-circle, with reflective paper lining the inside. The solar tubes were placed as close to the focal point as possible. The sun was shining during the whole test, leading to increase in the amount of heat transfer by 96%.

Solar evacuated tube efficiency

The efficiency of solar evacuated tubes has been advertised to be in the range of 50% (Bilgen, 2013). This is for an arrangement of several tubes aligned close to each other in a rack with little or no space between the tubes. In this study, the tubes were separated to 15.25 cm on centers and adapted with a reflective shield behind each tube in various configurations as described earlier in the paper. The effects of solar radiation (both direct and diffuse) imparted energy to the evacuated tube. In addition, there was radiation from the surfaces of the shields behind the tubes, which is also to be considered. Thus, energy received by the tubes includes the total solar radiation, the solar radiation reflected from the shields behind the tubes and the radiation emitted by the reflective shields behind the tubes. The temperature of the surfaces can exceed 65°C during the warm months and for the reflective surfaces with lower emissivity factors the temperatures may reach 43°C. This reflected and emitted radiation from the shields increases the amount of energy impacting the evacuated tube and may match the incoming solar radiation directly striking the tube. The efficiency of solar evacuated tubes was measured by direct water flow methods. The efficiency of each EST was calculated for each test using Equation (2) (Kreith et al., 2011).

$$\eta_{eff} = \frac{\dot{m} C_P \, \Delta t}{E_t + E_r + \dot{q}_{rad}} \tag{2}$$

An experimental run was made on April 13, 2015 with the 60° V-shaped reflector under sunny conditions in Morgantown, WV. The average energy output from the manifold was 296 w/hr., while the total energy incident on the three tubes was 490 w/hr. The thermal efficiency was 60.3 % and the ambient temperature was 22.2°C.

Taking the average experimental results of the flat black backing, the flat reflective backing, the 45° reflector and the 60° reflector and comparing to the control side with a flat wood backing showed a definite improvement in efficiency as shown in Table 2.

Table 2. Energy efficiency of the solar tube configurations

Date	Reflector Type	Experimental Efficiency	Control Side Efficiency
2/23/2015	Flat Black	71%	63%
3/2/2015	Flat Reflective	82%	48%
3/29/2015	45° V	42%	21%
4/13/2015	60° V	50%	41%
4/21/2015	60° V	51%	15%
4/23/2015	60° V	71%	63%
4/24/2015	60° V	64%	39%
Average		63%	33%

The table reflects results taken at various times during testing with four of the results from the 60° reflector, which seems to be the best performing. All tests covered a time period of approximately four hours, usually during the afternoon.

The improvement in efficiency over the control side indicates that having reflective backing for the tubes has a beneficial effect on the energy collection of the evacuated tubes. The testing reported here was done in sunny weather conditions with varying outdoor temperatures. During cloudy or rainy weather, the results did not show any difference as might be expected.

Effect of the reflective shields

The reflector configuration allows the radiant solar energy to be reflected back onto the rear side of the evacuated tubes. Depending on the solar azimuth, the back of the tube will have varying amount of additional solar energy provided. Figure 6 shows the amount of sunlit area on the rear of the tube, based on the solar azimuth for the 60° V-shaped reflector.

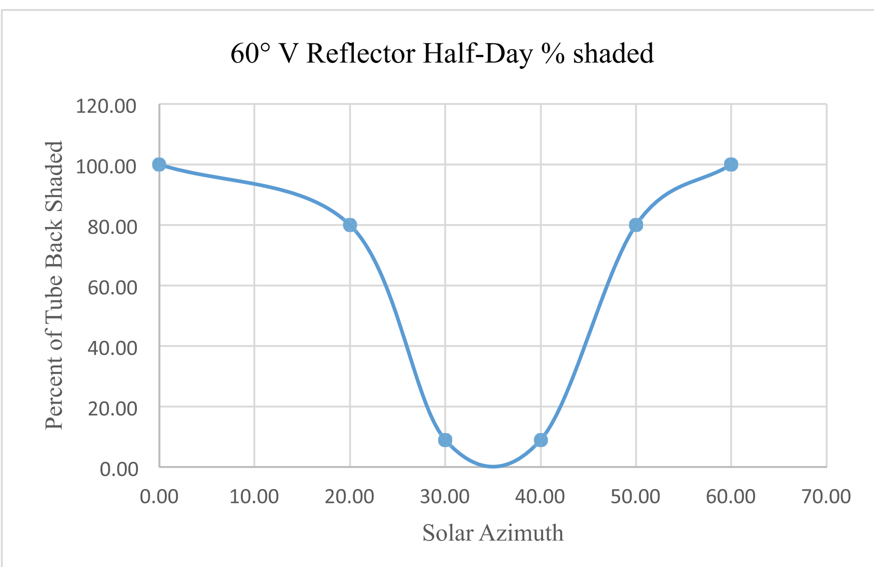


Fig. 6. Half-day back reflection on evacuated tubes for the 60° V-shaped reflector

In location where the testing was performed (At 40° north latitude), Figure 6 represents the shadowed portion on the rear of the evacuated tube, which was symmetrical during the noon period. Maximum reflection on the back of the evacuated tube occurred between 9 - 10 AM and 2 - 3 PM eastern daylight savings time. In addition, the radiation from the reflector surfaces adds more incident radiation to the rear of the tube. Its radiation is given by Equations (3) and (4). (Çengel & Ghajar, 2015)

$$\dot{q}_{rad} = A_{tube} F_{1-2}\, \varepsilon\, \sigma\, t^4 \qquad (3)$$

$A_{tube} = Area\ of\ the\ tube\ subject\ to\ the\ radiation$
$F_{1-2} = Shape\ factor\ between\ tube\ and\ radiant\ surface$
$\varepsilon = Emmisivity\ of\ the\ radiating\ surface$
$\sigma = Stefan - Boltzman\ Constant$
t = *Temperature of the radiating surface*

$$E_t = E_D \cos\theta + E_d \qquad (4)$$

E_D = *Direct Solar Radiation*
$\theta = Angle\ of\ Incidence$
$E_d = Diffuse\ Solar\ Radiation$
$E_r = \rho\,(E_D + E_d)\, F_{1-2}$
$\rho = Surface\ Reflectivity$
$F_{1-2} = Shape\ Factor\ Between\ the\ Reflector\ and\ the\ Tube$

The reflector was covered with a 3M Corporation reflective film having a very high reflectivity of 0.95. The shape factor of the reflector and the evacuated tube was also near one for the 60° V-configuration. Solar insolation and emitted radiation were reflected in the total energy received by the evacuated tubes. Figure 7 shows the evacuated tube insolation and energy received from the backboard surfaces for a typical test run.

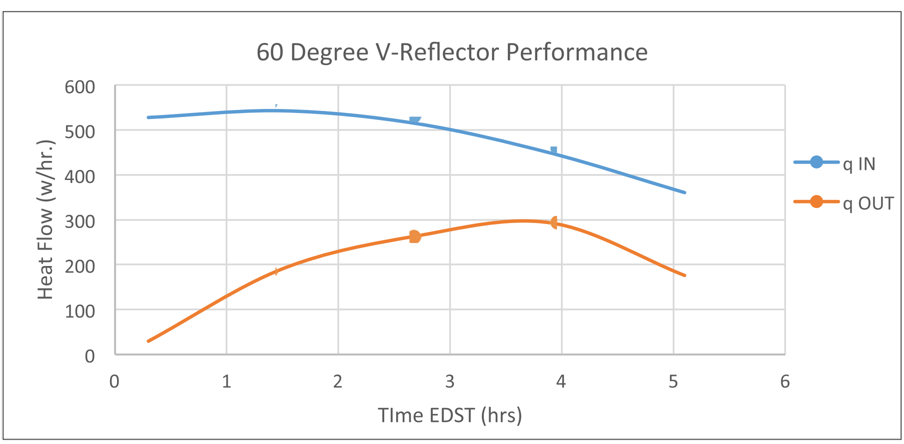


Fig.7. Energy Input to the evacuated tubes on a selected test run

Experimental uncertainty

The two variables that affected the accuracy of the energy collected by the manifold were the temperature and the mass flow of the water through the manifold. The thermocouples have an accuracy of ± 0.75% and the mass flow rate accuracy was ± 0.026 kg/hr. This gives an experimental uncertainty of ± 18% due to in large part by the thermocouple accuracy.

DISCUSSION

Traditional EST systems, where the designs do not integrate a back reflector are subject to loss of solar radiation absorption due to shadows and lack of sunlight exposure along the backboard facing half of the solar tubes. Different solar azimuth angles with reflectors could provide additional input energy to the rear portion of the tubes.

The black backing on the flat surface seems to yield an incredible change in heat transfer in correlation to a change in distance. This is most likely because the black surface is acting similar to that of a hot plate in that the solar tube's proximity to the hot surface affects its ability to draw in energy. As the light hits the dark surface, the black material absorbs the heat. The excess heat that the material cannot absorb then radiates off the material back towards the tubes. This explains why huge increases occurred as the backing was moved closer to the tubes. The downside to this is that, when it is cloudy, the black material can only absorb very little heat and in turn is not affecting the tubes as much as other configurations do under the same weather conditions.

The V-shape allows for excess light to be focused on the tubes from around the tubes. Seeing that the 45o produced better, when situated closer to the center of ETS, and the 60o when further away suggests that finding the center of the imaginary diamond that is created with the reflective walls (making up the bottom half of the diamond) would result in the proper distancing of the tubes, in order to allow for reception of most solar light. This would essentially be the focal point equivalent of the diamond. However, the side effect of this is that as the sun becomes lower on the horizon, the slanted sides that offered such production while it was able to collect light, will begin to cast shadows on the tube, as was noted in the heat transfer efficiency between the experimental and the control parts (see Figure 8). Essentially, the V walls will begin to block the sunlight that would otherwise be still making contact with the tube's sides. Therefore, increasing the space between the evacuated solar tubes will allow more room for the reflectors to receive sun light.

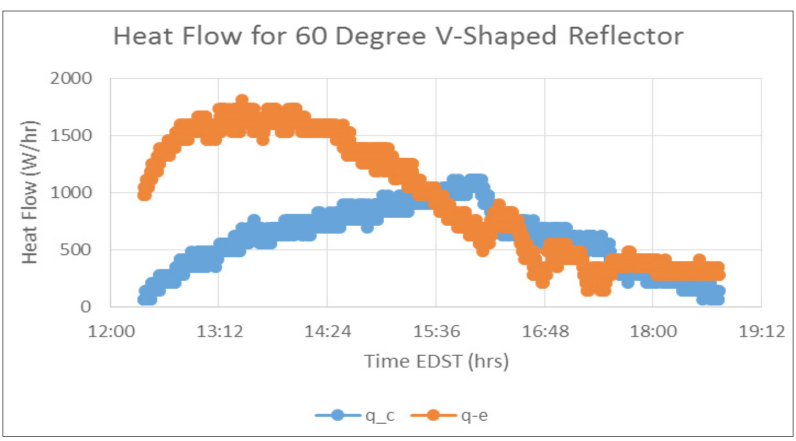


Fig. 8. Heat transfer data plot for the V-shape test

The energy emitted by the reflectors and flat back cannot be ignored in the efficiency calculations. For the reflectors with the 3M mirrored coating, the amount of emitted energy is less due to the low emissivity of the surface of 0.04. For the flat wood and black plastic covered surfaces, it is much higher due to the corresponding emissivity being in the range of 0.9 - 0.95 (Electro optical industries, 2015).

The half-circle configuration is very similar to the V-shaped configurations, when concerned with the negative effects of shadows cast by the solar tube itself. While the angle of sun is above the top edge of the circle, it produces more heat transfer. Since the tube must sit in the focal point to receive the reflection of the light, the tube is recessed halfway into the circle. This limits the amount of surface area on the tube that light can make contact with, and as the sun becomes lower in the sky, it will begin to cast shadows on the tube.

Through all the tests, another interesting piece of information was consistently noted. When sun was out, both experimental and control sides outperformed their counterparts of the cloud cover tests. However, commonly, the largest percent increases in heat transferred from the experimental side as compared to the control, occurred when there was cloud cover. It was thought that this occurred because the control was much more affected by the clouds when compared to the experimental side, which had modifications to collect as much sunlight as possible.

During the completion of the experiment, results showed that for evacuated solar tubes with 60°V-Shape at 15.25 cm, 189 watts of energy was conserved. Assuming a daily average of six hours of good (sufficient) sunlight, the hourly energy savings was determined by multiplying this saved wattage by 6 hr/day, equating to a total of 1.131 kWh/ day.

The test conducted utilized only three evacuated solar tubes, whereas most commercial collectors consist of 30 tubes. Therefore, a comparative analysis of the experimental system was conducted to relate it to the commercial collector. To do this, the 3-tube collector's equivalent energy savings of 1.131 kWh/day was multiplied by 10 to yield 11.31 kWh/day, which represent a 30-tube system. This resulted in a yearly energy conservation of 4,128 kWh/year.

Knowing the calculated power saved yearly by EST, we can finally determine the amount of CO_2 emissions that could potentially be saved if this technology were implemented. In order to calculate the CO_2 emissions saved the experimental EST, three-tube system was again compared to the 30-tube commercial model. The energy savings from the 30-tube EST system is approximately 11.31 kWh/ day, which equates to roughly 4,128 kWh/ year. Therefore, resulting CO_2 output emission rate is 7.03×10^{-4} metric tons CO_2 /kWh. From this it was determined that the reduction per system with 30 EST per year would be 2.9 metric tons per year (US EPA, 2010). Therefore, the experiment verified that the environmental effects of implementing these EST systems across various residencies would be very significant.

CONCLUSION

All of the tested configurations showed an increased efficiency in the amount of heat generated, when compared to the control configuration model. The two best choices were the 60º V-shaped configuration at 15.25 cm and the 45º V-shaped configuration at 10.20 cm. The biggest factor affecting reflector performance was the shading factor on the back and side of the solar tube. The 45°and 60° reflector angles gave the best efficiencies. However, the shallower 60° angle allowed more solar radiation on the tube at the late afternoon period, due to less shading of the bulb. The sensitivity of the results is close with these configurations but drops off rapidly at other angles.

For this reason, it is concluded that the 60º configuration is the most beneficial, as its wider angle will allow sunlight to enter the reflective valley for a longer period of time. The half-circle configuration was hurt by the previously stated issues regarding setting sun, which could be problematic for the 45º configuration as well.

In closing, EST is a promising renewable and safe source of energy, which harnesses the most abundant source of natural clean energy of our planet. It is environmentally friendly, energy efficient, and has a great potential to produce ample usable energy for the population, while reducing thousands of tons of CO_2 per year.

The idea of moving the entire solar tube system to orient with direct rays of sun has some merit. The graph in Figure 6 shows the shading effect of solar azimuth on a stationary solar tube arrangement. If the solar tube system could be oriented to face the sun at all times, the shadow on the back and side of the tubes would be minimized, resulting in higher efficiencies. This is definitely worth future study.

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