TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING

Department of Materials and Environmental Technology

ENHANCED EFFICIENCY OF A PARABOLIC TROUGH BY ROTATION OF THE RECEIVER

MODIFITSEERITUD PARABOOLIKUJULINE PÄIKESEKOLLEKTOR

MASTER THESIS

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AUTHOR’S DECLARATION

Hereby I declare, that I have written this thesis independently.

No academic degree has been applied for based on this material.

All works, major viewpoints and data of the other authors used in this thesis have been referenced.

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List of Abbreviations and acronyms

$\dot{m}$ is the mass flow rate of water in kg/s

C_p is the heat capacity of water in KJ/Kg.K

ΔT is the average temperature in K

A is the area of the tube in m^2

I is the radiation in W/m^2

A is the cross sectional area in m^2

I is the overall solar radiation available

U_L Is the overall heat transfer coefficient of losses = 7.15 W/m^2

TWh is Tera Watt per hour

MWh is Mega Watt per hour

KWh is Kilo Watt per hour

SDA is serial data analog

SCL is serial clock line

1. Introduction

1.1 Current State

Over the past years, energy resources was one of the highest priority concerns in the world due to the inevitable fact of continuous growth of world population against the fixed amount of resources that are available. As per the level importance of this matter, new organizations, protocols between countries and nations, rules and laws were established. The ultimate goal that they found as a common one is to switch from using non-renewable energy resources to renewable ones as soon as possible by investing money for research and time of scientists into this field.

Renewable energy defined as any source of energy that is coming due to a natural phenomenon that is never ending such as sun, wind, Waterfalls, waves etc. Solar energy is considered one the highest potential form of energy due to its availability globally and its consistency. Due to this fact, it has been the most form of energy that was under the scope of research and it developed rapidly specially in the past 10 years. Scientists and engineers introduced many new technologies of solar energy in order to satisfy different types of needs and to cover as many applications as possible.

This research paper will mainly focus on parabolic troughs, which is one of the oldest types of solar collectors used for solar energy collection. In the first section, I will discuss the different types of solar energy collectors known in the market these days. In the second section, I will mention the instrumentation used for the project and the experiment then the method or the process used in the experiment. The following section will be the parts and the design of the device used for heating. The coming part will be the experiment results, observations and calculations. Finally, in the last section, I will explain all the circumstances around the experiment and the process to conclude the outcome of the project.

1.2 Solar energy in Estonia

Although the sun days in Estonia is considered lesser if we only consider the amount of days where sky would be clear in Estonia along the year. However, due to the location of Estonia, in the summer it has longer days of light and can be considered among the longest ones in the world.

This is one of the factors that brought the attention of the Estonian government towards the potential of solar energy in the region. In addition, the country is located in the Northern Hemisphere between the Northern latitudes 59°40’ and 57°30’.

The total days of overcast in a year is about 180 – 200 in the North- and Southeast-Estonia and some 150 – 160 days in the coastal area of the Baltic Sea. The intensity of solar radiation is seasonally very different. The atmospheric circulation and the nature of the climate that it is in continuous change enhances the seasonal differences of solar radiation.

In December, when many cyclones go over Estonia, the sunshine duration is about 4 – 14% of the maximum. In June, the sunshine duration in some places on the coastal area goes up to 60% of the maximum, and in the inland of the country, the average is about 55%. Due to these factors, the monthly solar radiation is 172 kWh/m_2 in Tartu in June, but in December only 7.8 kWh/m_2. Table 1 below shows the average radiation per month according to the readings over the past 10 years. (1)

Table 1.2.1. The annual and monthly radiation in kWh in Estonia (1)

RADIATION (kWh)	Jan.	Feb.	March	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Horizontal (Q')	13	32	78	108	153	172	163	126	76	35	13	8	978
Facing Sun (Q)	28	57	134	161	214	241	226	181	119	64	25	18	1468
Slope 5°, South	14	34	84	112	156	174	165	130	79	38	14	9	1010
Slope 10°, South	17	37	90	115	158	173	166	133	82	41	16	10	1037
Slope, 20°, South	19	43	98	122	165	179	170	138	90	46	17	12	1097

In the above table is total radiation on horizontal and southern sloping surfaces in Estonia, as well As on a surface that is always turned perpendicular to the Sun's position. The chart below illustrates the distribution of direct, indirect and total sun radiation considering its distribution over a horizontal surface on monthly basis.

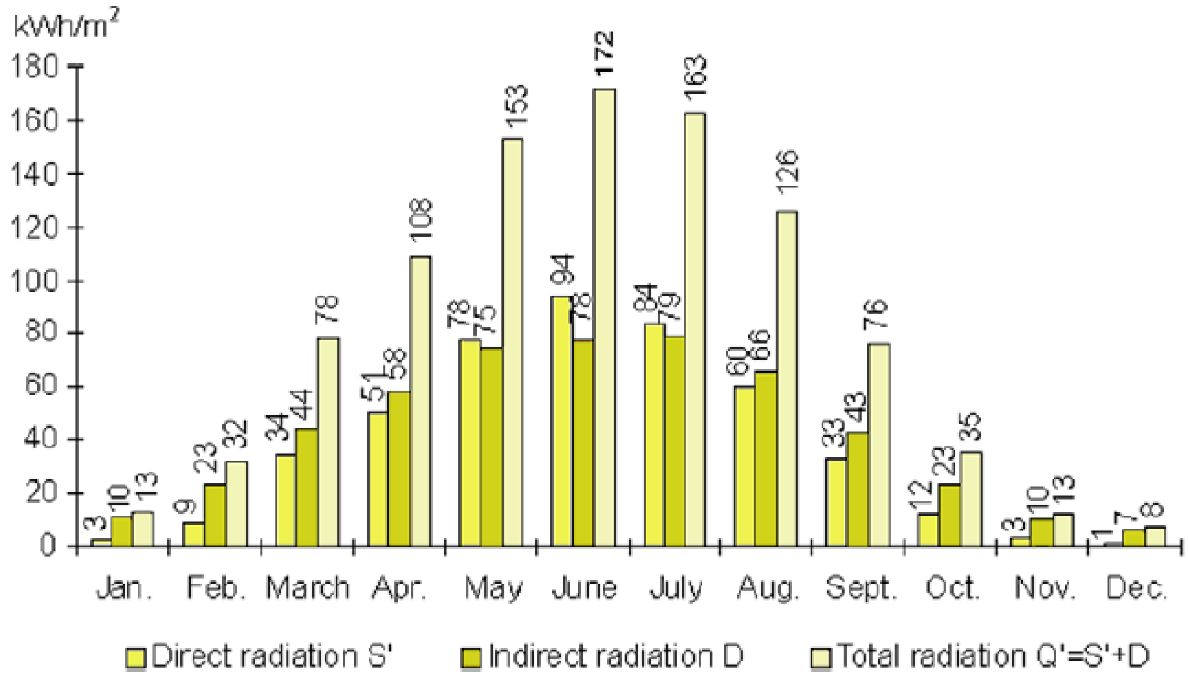

Figure 1. Monthly based radiation flows in case of horizontal surface. (2)

Estonian history is not involved much or does not include any experience in solar energy exploitation, except for the heat supply for greenhouses. The debut of use of solar energy took place about 22 years ago. In 1995, Vändra Hospital has been provided with a solar station to provide the needed energy for central heating system with the surface area of 40 m2. It was a proposed humanitarian aid from Swedish Nynäshammi Commune. The solar system is linked to the common central heating system of the building, run on fossil fuel. As a two-stage heat transfer system is used with antifreeze in the outdoor circuit, the system can be kept in service even in the wintertime. (2)

The biggest present solar heating system was commissioned in 2009 in Tallinn on the roof of a residential building, consisting of 64 solar panels with 1920 vacuum tubes. The cost of the project was 100 000 EUR, covered by a bank loan. The total surface area of the system is 255 m2 and the peak energy output intensity is up to 1 MW. The planned annual energy delivery of the system is about 250 MWh, resulting of fossil energy saving in fiscal units up to 15 000 EUR. The calculated payback period of the project is below 10 years. In addition to commercial projects there have been installed some homemade solar panels for space heating in private residential buildings all over Estonia. For instance, there is a 12 m2 surface solar panel on the roof of a private resident house in Nõmme, covering the heat need of the house for the most part of a year. Apart from the applications mentioned above, 36 lighthouses and naval signs uses photovoltaic modules which are buildings under the Estonian Naval Force.

Concerning scientific research on solar energy systems, Tallinn Technical University is doing research on the efficiency rise of thin film photovoltaic elements. Economically, the use of photovoltaic modules for generating power into the common grid is not feasible for Estonia. If the cost of 1 MW solar power is 2.1 million EUR, we get that the production cost of 1 MWh in Estonia is 300 EUR which surpasses the Nord Pool average price by six times. However, in the near future there will be 100 kW solar farm erected in Võru County in South-East of Estonia. (2)

The solar modules of this farm, mounted with tracking systems, will be placed on 6 m high poles. The company doing this project is called Energy Smart Estonia, which is a sub company to renowned Energy Smart. The cost of the project is estimated to be 400 000 EUR and factoring in planned 60 % donation, the calculated payback period of the project would be 16 years.

Producing domestic hot water in summer in Estonia is another potential for solar energy there. It is proven that by using solar energy usage, it is capable of covering about the half of all the domestic hot water need in Estonia. The savings of consumption can go up to 5 – 15 % if only used for producing hot water, but if it can also supply space heating, the total saving is estimated to be in the range of 20 – 60 % of household heat consumption The heat energy cost produced on the basis of solar energy is not higher than produced by other energy sources in Estonia and definitely it is lower than the cost of heat energy produced by electricity. (3)

The average hot water consumption in Estonia is about 50 litres per capita and day. This indicates that the heat energy need for domestic hot water per capita is about 4 MWh/year. As the Estonian adult population in Estonia is 1.1 million, we get that based on solar energy one can cover annually about 2 TWh of the heat energy need in Estonia, if all would use it in hot water supply. Considering that the technical solar heat potential in Estonia is 350 kWh/m2, the needed surface area for producing 2 TWh solar heat, would be 5.5 km2. However, in 2000 the surface area of dwellings in Estonia was 35.8 km2. Therefore only 15% of total roof area of dwellings is needed to produce this amount of solar heat and this is rather realistic to achieve without resorting to some complicated construction work for installing the needed solar heat panels.

We can conclude the solar heat energy annual potential in Estonia to 2 TWh. On the other hand, theoretically, all of this could all be used for domestic hot water, realistically it would be used for a range of applications, including domestic use, service sector including swimming pools, and industries that use low-temperature heat. Considering that the solar photovoltaic energy efficiency potential in Estonia is 100 kWh/m2 and covering 20% of the area of roofs in Estonia, The result we can get from this is that the solar photovoltaic power potential in Estonia will be about 0.7 TWh. 3. (3)

1.3 Types of solar collectors

1.3.1 Solar panels

Various devices are there nowadays for collection of solar energy which are used in its different applications. The first device and commonly known one is the solar panels, which is the most commonly known method and considered the first one introduced by engineers for the purpose of solar energy collection.

Figure 2. Solar panels manufacturing. (26)

The cells are square shaped cells and are made of crystalline silicon or thin film cells made of cadmium telluride. The process of solar panels manufacturing has some standard steps that are commonly followed by manufacturing companies, the following diagram shows the steps and their sequence.

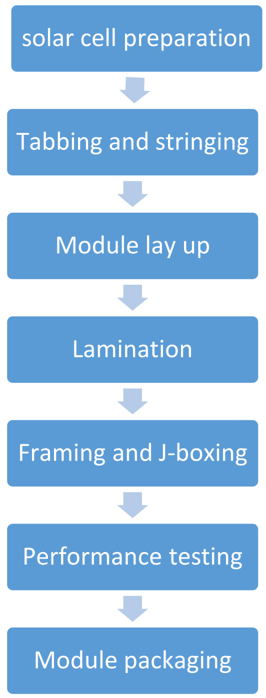

Figure 3. Manufacturing steps for solar panels production. (4)

The first step, which is the checking, includes a check that is done on the cells for the voltage and current to make sure that there is no damage in them. The tabbing and stringing process is the one in which flat metal leads are soldered to the contact leads which occur on each PV cell then those cells are connected in series and soldered in strings which is called the stringing. The next step is the one in which the strings are put in the desired order and each string is connected with bus ribbons to the other to make a PV module , then these modules are cleaned thoroughly to be prepared for lamination using low-iron glass , EVA and Tevlar layers. The fourth step is the lamination, in which the PV laminator connects the several layers of materials with thermoplastic film, and the process is done in a vacuum medium to ensure the complete encapsulation of the parts. The next step includes the trimming of the module and framing it using an aluminium frame and then an electrical connection junction box is added at the back of the frame which will be used to connect the module to another one or any application. A performance test is required after that to make sure that the module is operating well and in good condition, this is done using a sun simulator. In the end, the modules are packaged and ready to be used in PV-systems. (4)

1.3.2 Parabolic troughs

This collector uses solar thermal concept for electricity production or heating purposes. It consists of three parts , in one dimension there is a tube in which a fluid flows and gets heated using the sun rays , the other two dimensions has a curve shaped parabola polished as a mirror to collect the sun rays onto the tube. The tube is always mounted in the trough at the focal length to ensure maximum efficiency of heating.

Figure 4, Standard Parabolic trough. (20)

This is heat is either used directly in heating as mentioned or it use used to heat up water and turn it to steam to run a turbine for electricity production. There are mainly four reasons why the focus on the parabolic troughs is high in developing them and to increase the number of solar power plants operating with their concept:

The development of green power markets shows the high potential of parabolic troughs to be used in the future as an alternative energy.

Economically, compared to its potential, it is considered to most preferable method to be used in solar energy power plants several financial studies was made on the parabolic troughs and showed that it is the most likely collector to have a significant cost reduction in the near future the ease of its maintenance and its estimated life of operation gives it another bonus as well.

The manufacturing of parabolic troughs is not really under the spot of focus nowadays for development as the solar panels are not much dependant on the outer temperature yet just the sun light.

The sides of the reflector are extended upwards and the interior center of it is stretched to the surface of a male mold fixture. Fixing a parabolic bow at the sides of the interior mirror and fastening the said bows to the said sides to form an integral channel an external parabolic channel is stretched and positioned above each of the interior parabolic mirror connecting the bows to the channels. Finally attaching edge channels to longitudinal edges. (4)

1.3.3 Parabolic dishes

This collector is unique due to the wide range of sizes of it and the better ability of concentrating the coming sunlight in one focal point.

Figure 5. Solar Dish by Tessera Solar.
(21)

The idea is originated from the dishes with antennas that are used to focus radio waves. The reflection of the rays by the dish comes from two sources. The first one is totally reflecting the rays parallel to the axis of the dish's axis towards the focal point regardless on which part they fall on the dish. The second prospective uses the fact that the sunrays are almost all parallel, so if the axis of the dish is adjusted to align with them almost all of the light coming is reflected to the focal point. The losses that occur in the parabolic dishes mostly occur due to the imperfection in the shape of the parabola or some reflection losses. (6)

1.3.4 Solar towers

The idea is similar to that of the troughs and the dishes, yet the power plant layout is so different as the collector is a huge tower built in the middle of flat mirrors which focus the sunlight on this

Figure 6. Solar Tower. (22)

tower for the aim of heating water to produce steam to run a turbine. The old designs of these towers are the ones using water; the more advanced designs use liquid sodium or other molten salts such as potassium nitrate or sodium nitrate. These alternatives are used due to their high heat capacity, which gives them the ability to store energy enough to boil water, and then used with the turbine. The design of such power plants is common , the only variations that might occur is in the cooling system for ones in the desert , as air is used instead of water to avoid water consumption. In addition, the control system used for the plant might vary from one to another. Thermal storages are used for the molten salts to keep them heated even during the absence of the sun. The steam should be heated at least to 500℃ in order to run the turbine. (6)

2. Literature review

2.1 Ivanpah power towers

One of the biggest solar power stations in California, located 40 miles southwest of Las Vegas. Based over an area of 3500 acres and the power output of the plant is 392 MW, which was developed by Brightsource energy. The project is divided into three separate plants and are currently fully operating,

Figure 7. one of the three towers in Ivanpah power station Taken by author

The power plant supplies electricity for more than 140000 homes in California during peak hours of day. Thousands of mirrors are mounted there to reflect the sunlight on a receiver which uses this amount of heat to generate steam out of water stored in the towers which is used to turn a turbine for electricity generation. (5) (8)

2.12 Nipton power plant

It is situated on a distance of 2 miles ahead from the Nevada-California border in east San Bernardino County. It provides 85% of the electricity needs of the residents living in Nipton by producing a power output of 80 KW. This percentage is the highest solar electricity production among any small town in the United States.

Figure 8. Nipton power plant. Taken by author

The plant is mainly consisting of panels, reflectors and single axis tracker.

The panels are manufactured with similar materials and processes as solar traditional solar panels, in fact that they are much smaller in size equivalent to the power production. High efficiency mono-crystalline silicon cells are used to maximize the energy produced from the concentrated light. The reflectors are used to concentrate the coming light from a large aperture onto a smaller surface area of the panels. The single axis tracker supports the reflectors by following the arc of the sun during the day over 170 degrees. The commonly known trackers have only 90 degrees limit. (5)

2.2 Nevada solar one

This plant is in Eldorado valley southwest of boulder city in Nevada and built over 400 acres of land. The nominal power output of the plant is 64 MW and the maximum power output is 75 MW.

Figure 9. Nevada Solar one power plant. Taken by author

Moreover, it can be considered as the biggest solar thermal energy plant built since 1991. The plant consists of parabolic troughs and solar concentrators, it has 760 parabolic troughs with more than 182000 mirrors to concentrate the sun radiation on 18240 receiver tubes placed at the focal axis of the troughs which and contains a heat transfer fluid. This fluid heats up to 391℃ and used to produce steam which is utilized in running a turbine to produce electricity. (5)

2.3 Some developments in parabolic troughs

A new idea was tested which was about using secondary reflectors are mounted to the parabolic troughs and these are simple collecting lenses that are used to increase the focus of the sun light on the receiver which are mounted inside the glass coating.

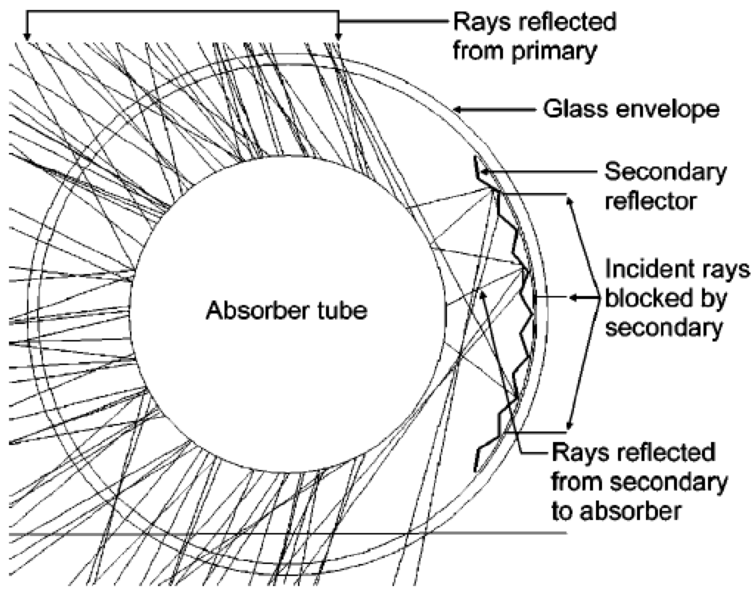

Figure 10. Secondary internal reflector cross section. (8)

The testing of this method did show a result of an increase of 2% in the annual performance of the field. The estimated cost of this new idea was $60. The project was considered not feasible and not sufficient compared to its cost; however there are some other benefits for this modification. It was recorded that the flux uniformity around the absorber significantly improved. In addition, the tolerance of the parabolic trough designs to optical errors increased. The following figure explains the modification in details and shows its effect on the incident rays and how it is implied to the receiver. (9)

Other studies were also conducted about finding a better heat transfer fluid in order to have higher temperatures for steam production. Earlier, when parabolic troughs were introduced to the market, hydrocarbons were used as thermal fluid. On the other hand, there were always limitations on the temperature they can reach as they don't work well at temperatures higher than 750°F. Thus, researches were initiated aiming to find other alternatives and then it was successfully done by finding out that molten salts could act as a more efficient heating thermal fluid. It has mainly two advantages over hydrocarbons which are:

- They can operate at higher temperatures (up to 930°F)
- The new heating storages systems that operate with molten salts is perfectly integrated with troughs using them as heating thermal fluid

A fact about molten salts that they are more corrosive than hydrocarbons so it required a modification in the design of parabolic troughs. This change was applied by adding new coatings and glass to metal seals in order to be able to with take the high temperatures and level of corrosiveness of molten salts. (8)

2.4 Sky Fuel parabolic trough

U.S. Department of Energy's National Renewable Energy Laboratory (NREL) started a wide test for available parabolic troughs in the market, which proved that SkyFuel's parabolic trough solar concentrator has the highest efficiency among all available similar devices. The utility scale parabolic trough solar concentrators harness the sun's energy to make steam for electricity generation. Patterned after the best of previous, time proven designs, the SkyTrough is a breakthrough in cost and constructability resulting from significant design and material innovations. The SkyTrough® is the first utility scale solar concentrator to employ lightweight ReflecTech® Mirror Film, developed collaboratively by SkyFuel and NREL, in place of the fragile glass mirrors traditionally used.

Thermal efficiency can be defined as the proportion of available sunlight that is converted into heat and available to generate electricity in the power block. It is used to measure the performance of a given parabolic trough and compare competing technologies. NREL tests show the SkyTrough's thermal efficiency at 350 °C (662 °F) to be over 73%, in other words, about three quarters of the solar radiation incident on the trough surface is converted into thermal energy. NREL's results confirm that the SkyTrough delivers performance better than any previously known one, with a cost below industry standards. "A lot of thoughtful engineering went into the SkyTrough so we were confident our efficiency would be high, but NREL's confirmation really validates our technology. We couldn't be more pleased with NREL's assessment", said Randy Gee, SkyFuel's Chief Technology Officer.

NREL scientists created an analysis for the results of two tests to establish a collector's thermal efficiency. Performance of the optical elements of the trough depends on the Optical Efficiency tests that were carried in Golden, Colorado. The test facility design allows study of the optical performance independent of the receiver's heat loss characteristics. Optical efficiency is a direct gauge of the design elements that set the SkyTrough apart - mirror reflectance, parabolic accuracy, receiver alignment to the focal line of the trough, and the system is tracking precision. "The SkyTrough solar collector is a new, low-weight design that takes advantage of the patented reflector film jointly developed by SkyFuel and NREL," said Chuck Kutscher, Principal Engineer and Manager of NREL's Thermal Systems Group." Helping industry achieve higher efficiencies and lower costs is central to the mission of our Concentrating Solar Power (CSP) research program."

Another test also NREL's Parabolic Trough Receiver heat loss test Stand, scientists measured the heat loss from the SkyTrough's SCHOTT PTR80 receiver. This is important because, it does not

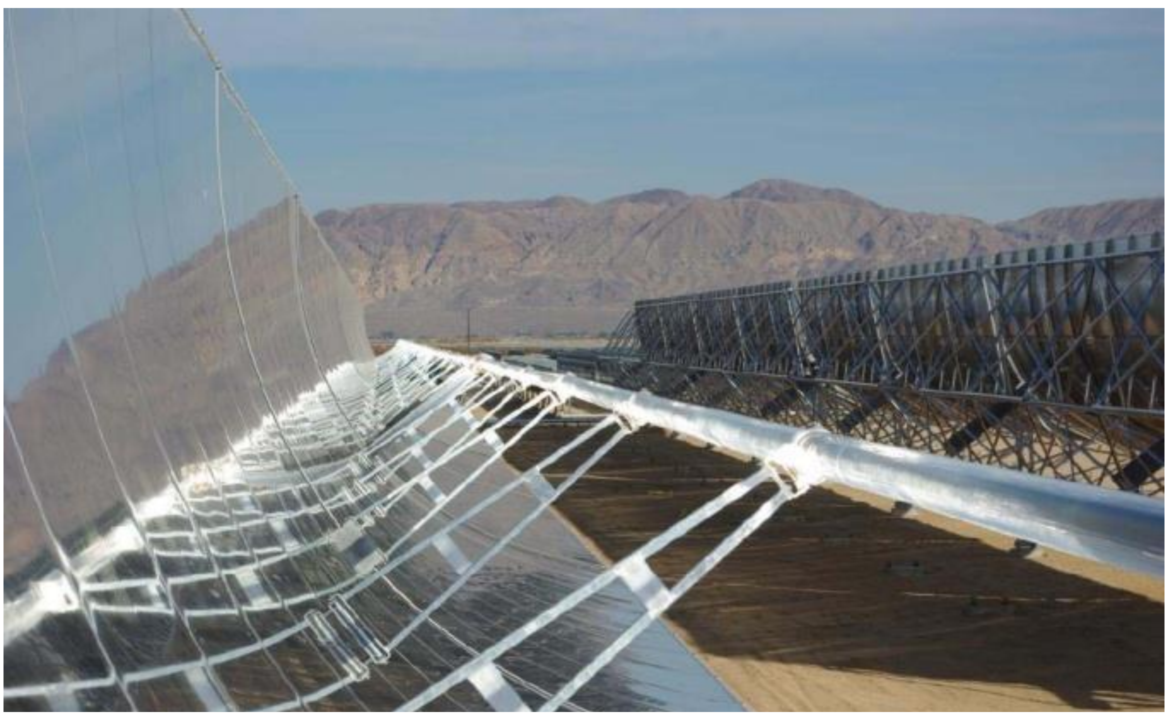

Figure 11. Skytrough SCHOTT PTR80. (34)

matter how well the SkyTrough's optical elements perform, the overall ability of the system to deliver usable heat for power generation depends on how well the receiver retains the heat it collects. The new 8 cm diameter receiver produced good results compared with SCHOTT's 7 cm PTR70, the current industry standard for utility grade parabolic trough systems.

2.5 Top Alignment method

One of the world's biggest parabolic troughs power plants, located in the Mojave Desert near Barstow, Calif., consist of nine plants producing 354 megawatts of power at peak output. It has an output of 14 to 80 MW. The 30 MW plants near Kramer Junction, for example, each have about 10,000 modules with each module comprising 20 mirrors. A 64 MW trough plant, which will supply power to Las Vegas is operating. A 1 MW plant also exists in Arizona. An issue with parabolic trough systems was the lack of accurate mirror alignment that prevents maximum energy efficiency.

As per methods used to align mirrors in solar dish systems, new method was established called TOP alignment, through which an evaluation of the alignment of mirrors in parabolic trough power plants and apply corrective actions. "This method could be used during trough power-plant construction to improve the performance of existing power plants or for routine maintenance," Diver says. "It should be an ideal mirror alignment technique because it is simple to set up, requires a minimum of sophisticated hardware, and does not require removal of the receiver." (11)

The TOP approach works by mounting five cameras positioned along the plant. Four of the cameras take digital photographic images of the four rows of mirrors that focuses on the module. The middle camera photographs the module's center, where a boresight gauge is placed, which is used to vertically center, the pole to the trough module. Methods from vector algebra and projection sciences are used to predict the theoretical projected image of the receiver for perfectly aligned mirrors.

The calculated theoretical image of the receiver for perfectly aligned mirrors is overlaid on the photographs of the actual receiver image position in the mirrors. The images and the actual image are compared to show how the mirrors should be aligned. It then becomes a matter of adjusting the mirrors to the correct alignment. "This whole process is very simple," Diver says.

"Once the mirrors are aligned, the energy savings start. It is like picking money off the ground. And the mirrors are aligned for the life of the plant." In order to check the needs in a power station in California, they mounted a fixture at the top of a trailer pulled by a government van that can be driven on highways to parabolic power plants. The cameras will photograph the modules at the different plants. Then the images are processed to check for possible alignment adjustments which can be done even while the station is operating.

3. Mechanical design

The design of the trough was based on the focal point of a parabola at 90 degrees curvature. All other dimensions are dependent on this to make sure that the receiver is exactly onto the focal point of the mirror. There were some errors in the dimensions during the manufacturing process as the device was hand made using simple machines, yet the design was made in a way that the arms holding the receiver would be adjustable in order to move the receiver freely to be adjusted according to sun positions and with changing the angle of elevation of the mirror and depression.

The materials selection for the trough was based on the factors listed below:

1. Cost
2. Environment
3. Nature of atmosphere in Estonia

The parts of the body of the trough were made of wood and compressed carton. This was the cheapest option for that part of the design yet due to the windy nature of Estonia, more dense types of wood and carton were used to make sure that the device would be stable when used and fixed at the required angle for taking the measurement.

Normally, the trough body is made of reinforced steel for a longer life of operation, however this is was not necessary in our case as the device is meant for testing only. The mirror part was made of stainless steel for reflectivity and strength. Also, stainless steel has the require ductility for bending it to the required angle of curvature for the mirror. Moreover, it has lesser wear factor and resistant to rust and physical damage in case of high impact during transportation.

The receiver is made of copper as it has high heat conductivity so that it would transfer the heat to the water running inside and it is cheaper compared to other metals with good conductivity characteristics.

There are three steel bars which were used to hold the parts together. Two bars are used to keep the legs together from the bottom as they are the main support for the whole body and one bar was used to connect the mirror, the arms and the top of the legs together. The following sketches shows the front, top, bottom and three dimensional views of each part in the trough.

3.1 Arms

The arms is the one of the most important parts of trough as the length of the arms represents the focal length which allows the the reflection of the sun rays to be exactly on it. There are two holes placed on the arm, one for holding the receiver and the other for the support shaft on which the mirror and the top of the legs will be mounted as well. Figure 11 which is represented below shows the sketches for the arm with its dimensions

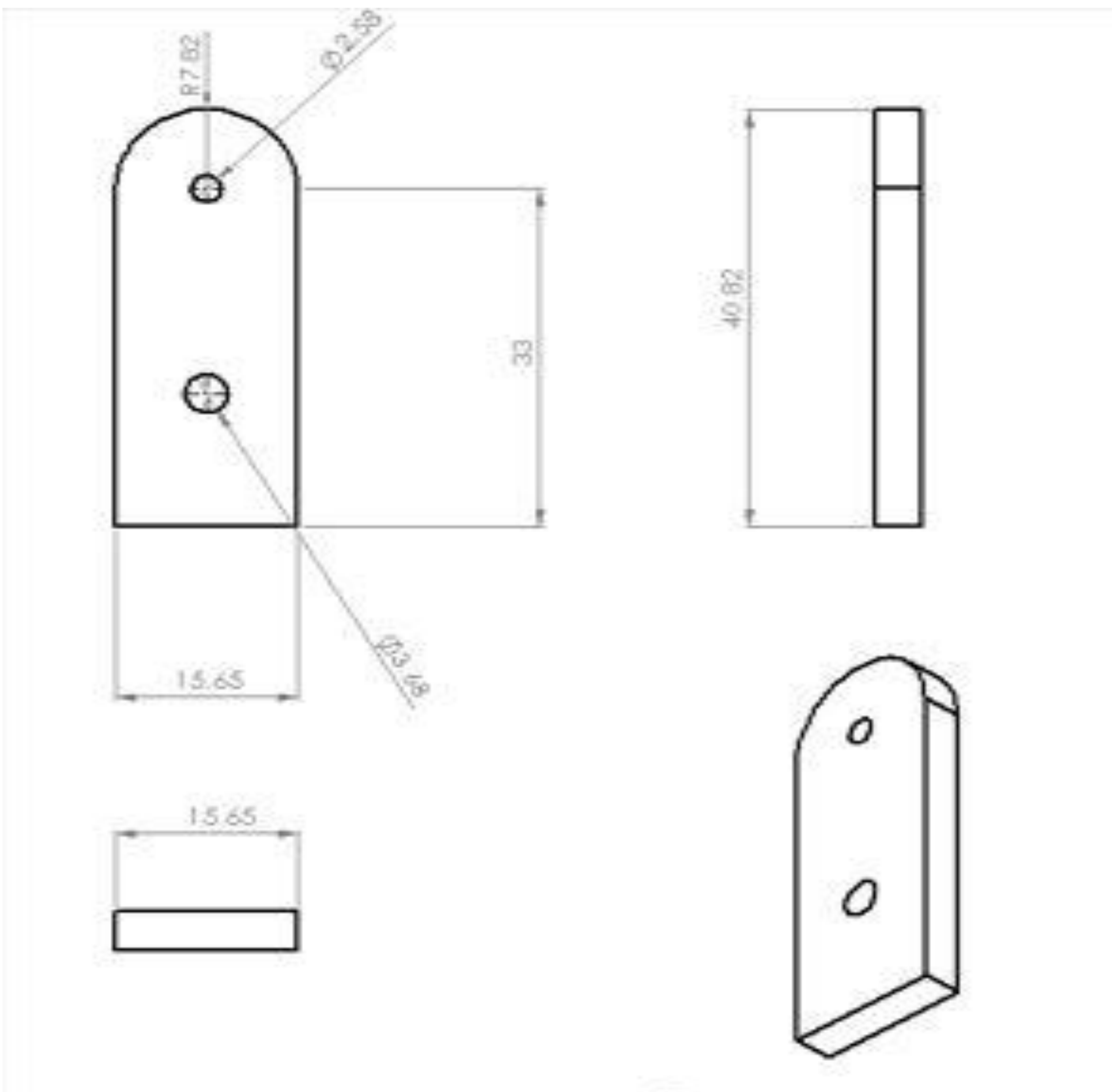

Figure 12. Arms. Designed by author

3.2 Legs

The legs are designed with a triangular shape for a standalone trough. The two holes at the bottom are for steel supports which would hold the legs together. The legs height was decided based on the height of the mirror and also in a way that it would be easy to reach in case of adjusting its position during the assembly. Figure 12 shows the sketches for the legs part with the dimensions.

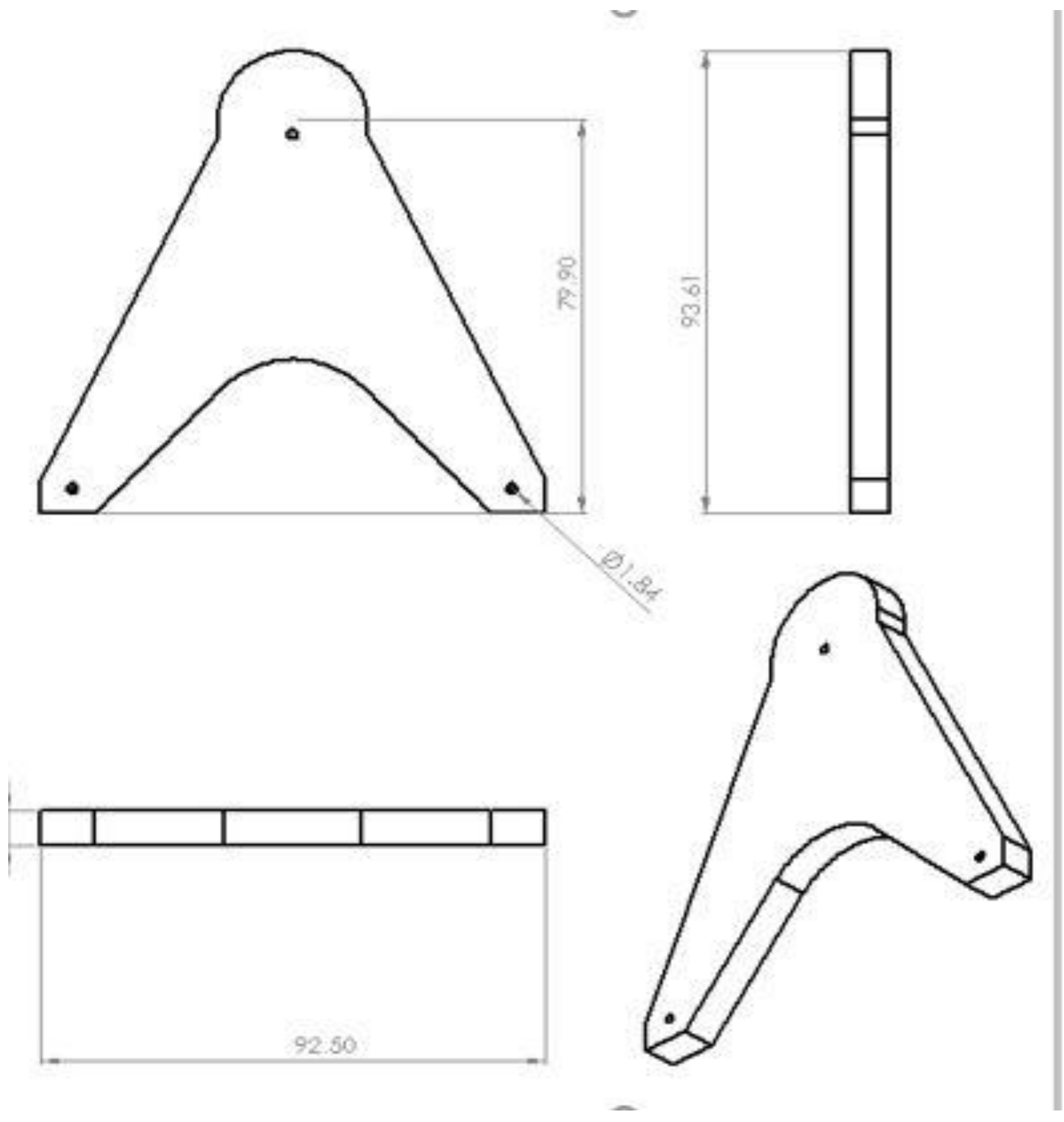

Figure 13. Legs. Designed by author

3.3 Mirror

The mirror angle of curvature was assumed as the very first step of the design. Based on this assumption, the other dimensions were decided. The width of the mirror is the dimension that affects the overall efficiency of the device as this determines how big the area of the reflection is. As the device is meant for testing purposes and to reduce the cost of delivery of the device, the width was selected as shown below in figure 13.

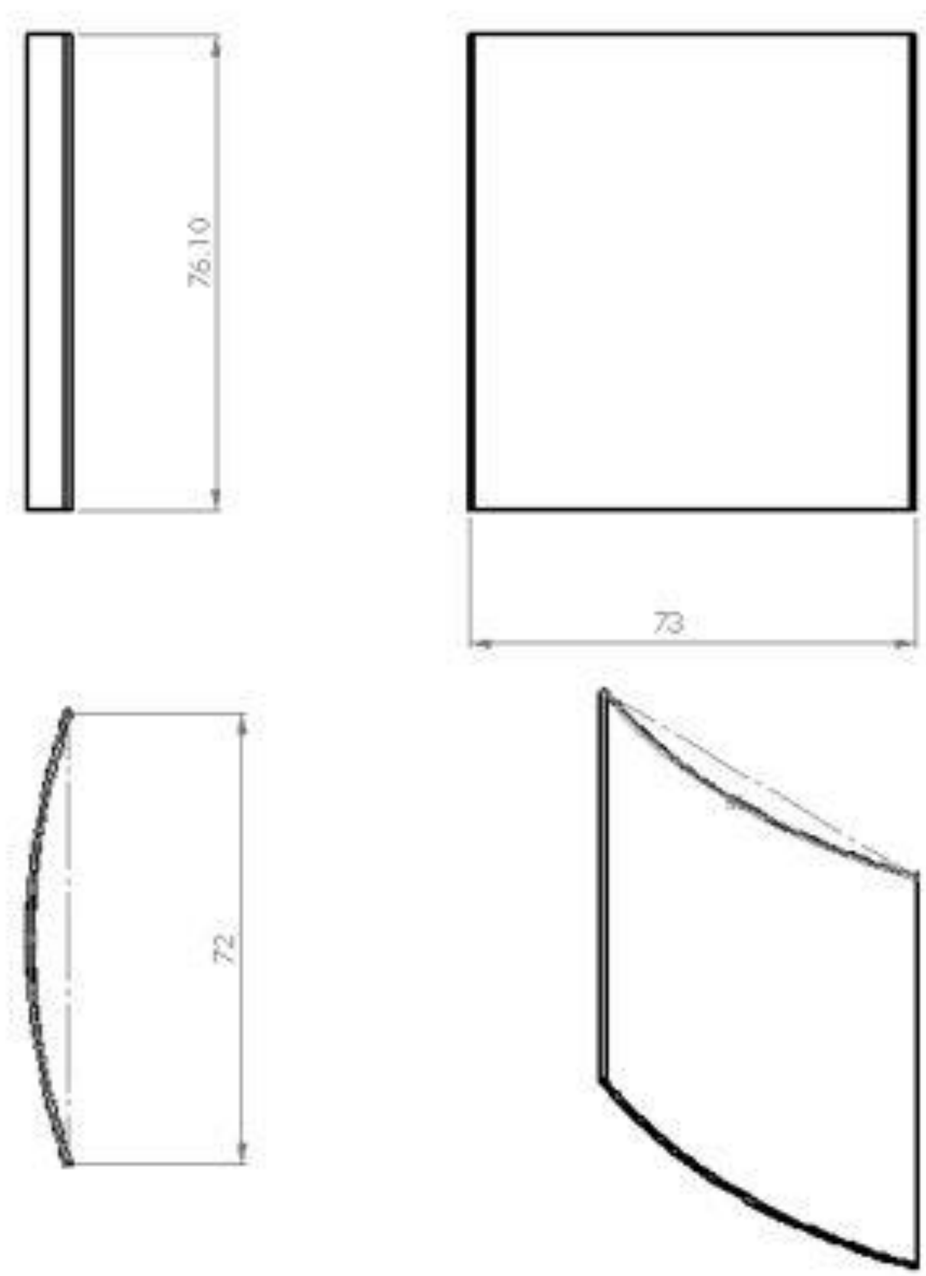

Figure 14. Mirror. Designed by author

3.4 Bracket

This part is the one used to hold the mirror and attach it to the other parts due to the fact that the mirror is a thin metal sheet so it cannot be attached to any other part without the bracket. It contains the hole in the middle through which the metal supports passes which also connects it to the legs and the arms. Figure 14 represents the sketches for the brackets with the dimensions.

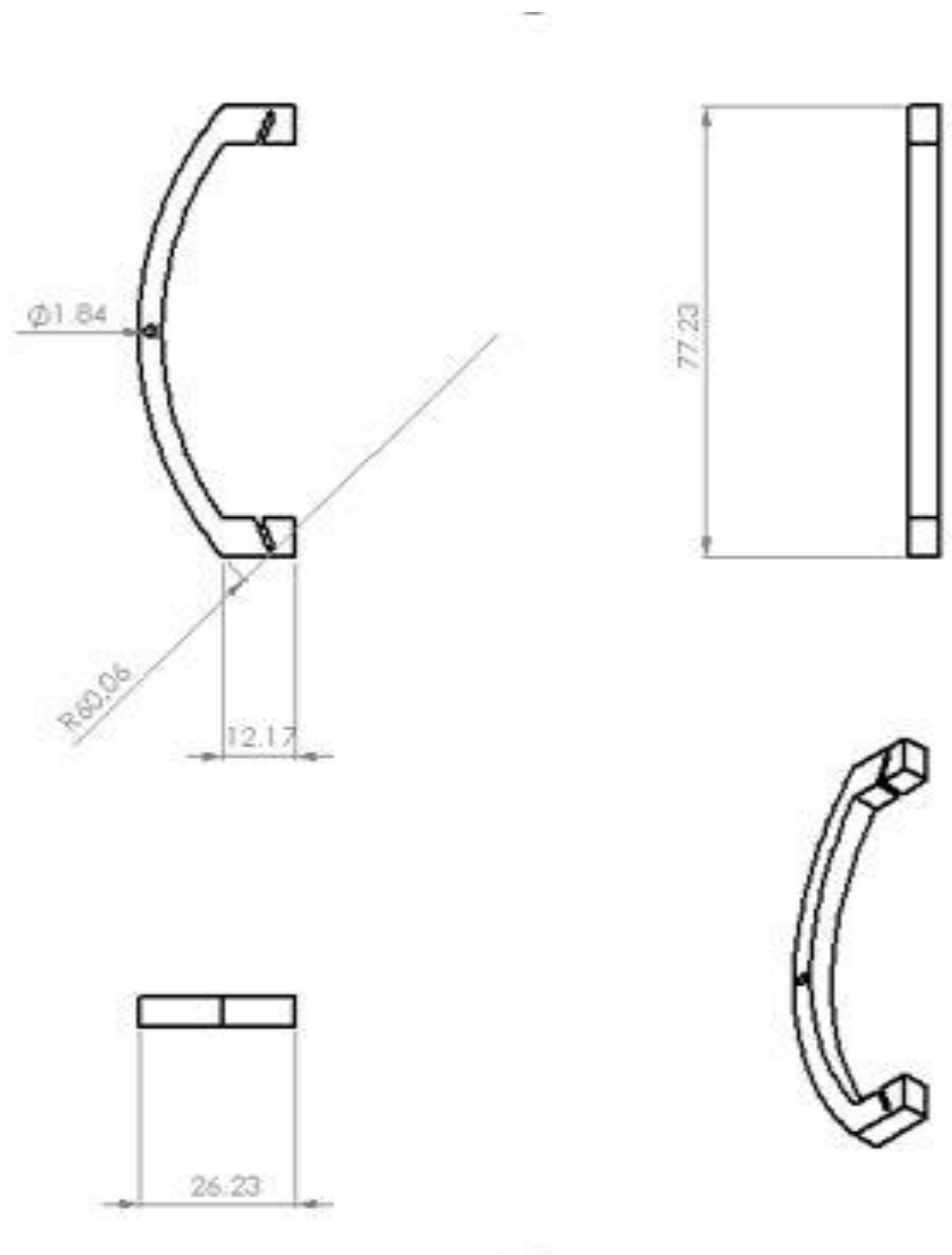

Figure 15. Brackets. Designed by author

3.5 Receiver

The receiver length have the same impact as the width of the mirror as this is the part through which the liquid to be heated passes, so the longer it is along with the width of the mirror, the higher is the efficiency of the trough. The diameter of the receiver is small to reduce the heat losses during conduction and convection processes which occurs when it is delivered to the liquid to be heated. Figure 15 shows the sketches with the dimensions of the receiver.

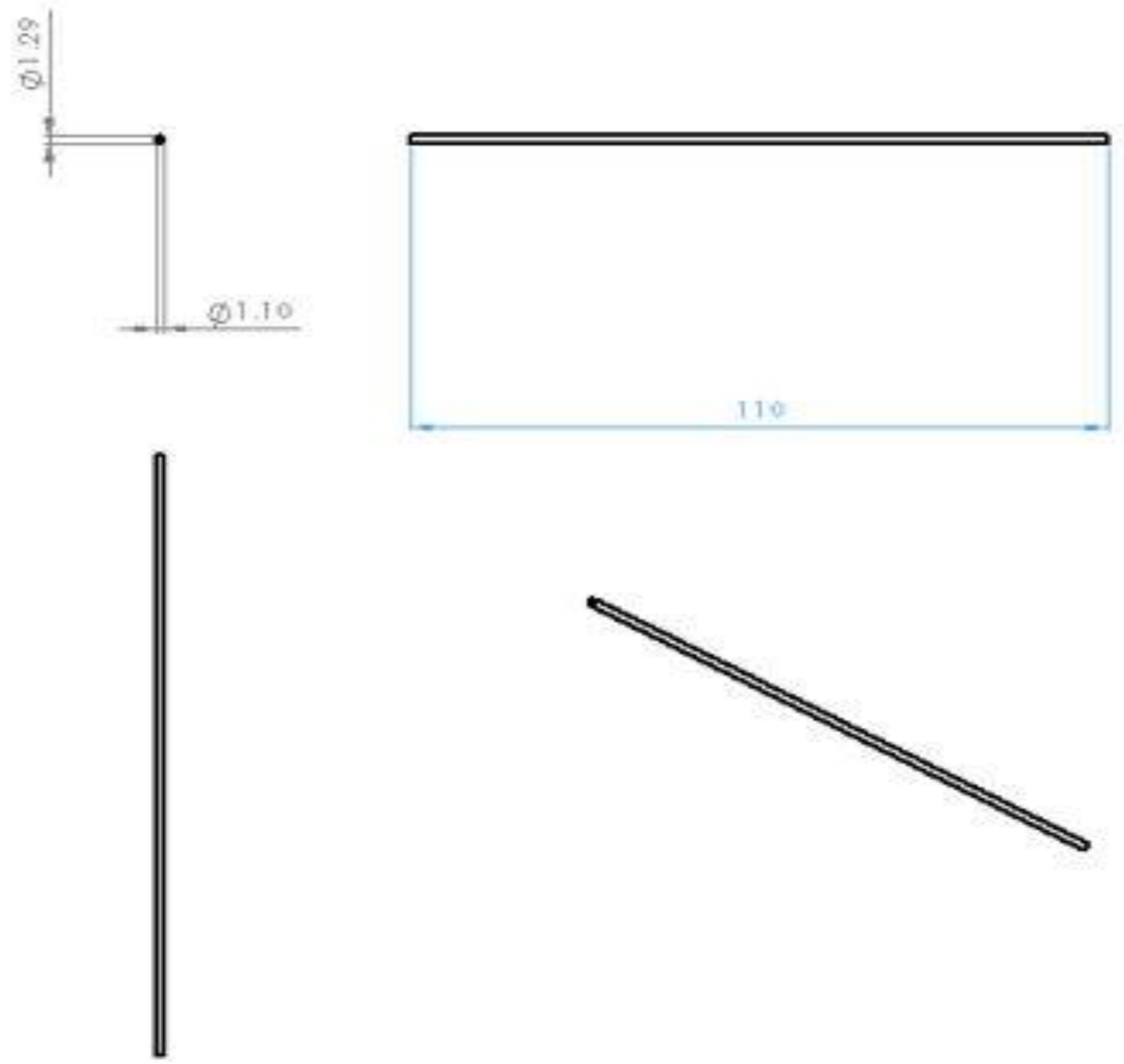

Figure 16. Receiver. Designed by author

3.6 Assembly

The last figure for the mechanical design is listed below which shows how the trough look like after all parts are assembled together.

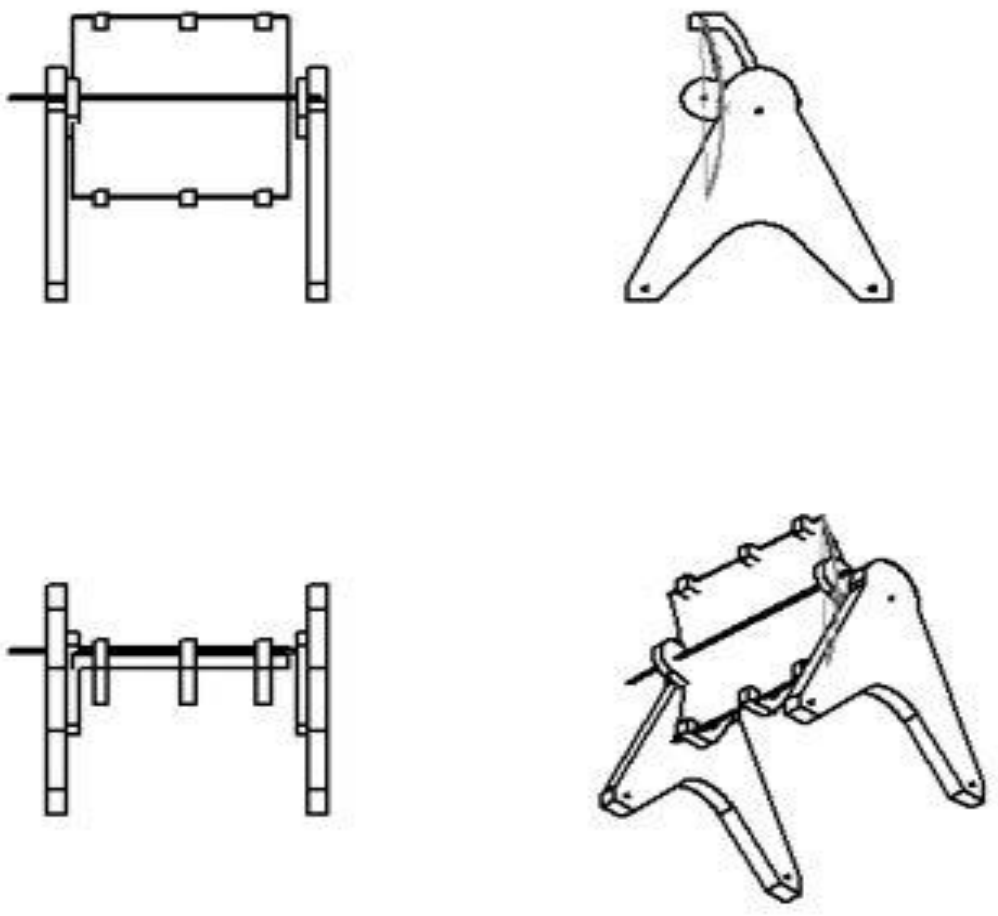

Figure 17. Assembly. Designed by author

The design was completed using solid works mechanical design software. The dimensions were applied based on a manufactured trough that was designed for testing during an internship I had in the United States. The main calculations applied for such design are for optical mirror to get the distance between the receiver and the mirror. The other dimensions do not impact the design much as they do not interfere with the focal point of the mirror. Thus, the dimensions of the legs, receiver, brackets and supports were just assumed based on the size of the mirror and its angle of curvature.

4 Instrumentation

There are different equipment required for the process of the experiment in order to have all the parameters required for the calculation of the efficiency and the effect of the newly applied modification on the design.

4.1 Arduino Temperature sensor

Arduino controller was used for temperature measurement at inlet and outlet of the receiver. The components of the circuit are as follows:

4.1.1 Arduino wiring connectors

The Arduino wires are simple copper wires with metal pins at the end, which are used to connect the components of the circuit. Eight wires were used to connect the wires of the sensor on the breadboard to the Arduino board, which are the ground wire, power wire and data wire. Figure 17 shows the wires that were used.

Figure 18. Arduino connectors. (11)

4.1.2 DS18b20 water proof temperature sensor

The Arduino sensor is the one used for measuring the inlet and outlet temperatures of the receiver. The sensor is covered by high heat conducting metal in order to make sure its response time would be as less as possible. The cover is added to make the sensor waterproof otherwise, it would malfunction. Figure 18 shows the temperature sensor used for the measurements.

Figure 19. Arduino Waterproof Temperature sensor. (12)

4.1.3 4.7 k□ resistor

The resistors are an essential part of the circuit to make sure that the flowing current is the one specified for the sensor as well as the board. It is placed in parallel to the sensor data and power wires on the breadboard. Figure 19 below, shows the shape of the resistor that were used in the circuit.

Figure 20. Resistors. (13)

4.1.4 UNO R3 ATmega328P USB-B Arduino controller

This is the new Arduino Uno R3. In addition to all the features of the previous board, the Uno now uses an ATmega16U2 instead of the 8U2 found on the Uno (or the FTDI found on previous generations). This allows for faster transfer rates and more memory. No drivers needed for different operating systems. (15)

The Uno R3 also adds SDA and SCL pins next to the AREF. In addition, there are two new pins placed near the reset pin. One is the reference that allow the shields to adapt to the voltage provided from the board. The other is a not connected and is reserved for future purposes. The Uno R3 works with all existing shields but can adapt to new shields, which use these additional pins.

Two boards were used, as there was two circuits used for taking the measurements, which are at the inlet and the outlet. Figure 20 shows the Arduino Uno R3 board that was used.

Figure 21. Arduino Board. (14)

4.1.5 Bread board for connections

The breadboard is the base of all components connections and it consists of a plastic cover with holes through which pins of the connectors are placed. Figure 21 shows the breadboard used.

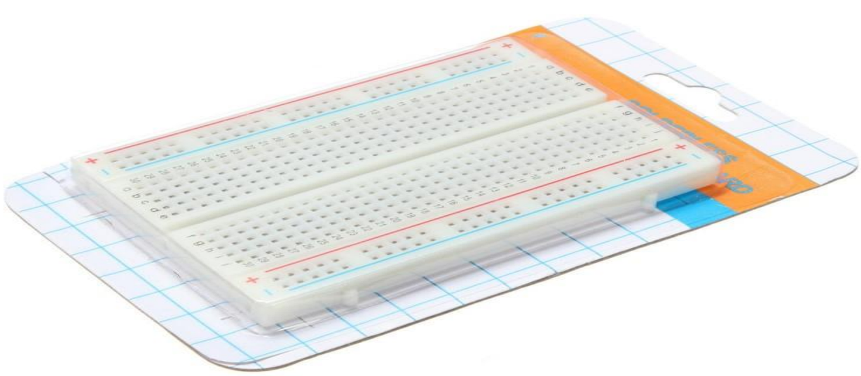

Figure 22. Breadboard. (13)

These components were used for the circuit and the code for the sensor is as shown below. The code was made to have the measurements done each second for the accuracy of the readings then the averages were used in the results and presentation of the temperature changes on the charts. The circuit after being connected is shown in the figure below:

```
/***************************************************************************/

// First we include the libraries

#include <OneWire.h>

#include <DallasTemperature.h>

/***************************************************************************/

// Data wire is plugged into pin 4 on the Arduino

#define ONE_WIRE_BUS 4

/***************************************************************************/

// Setup a oneWire instance to communicate with any OneWire devices

// (not just Maxim/Dallas temperature ICs)

OneWire oneWire(ONE_WIRE_BUS);

/***************************************************************************/

// Pass our oneWire reference to Dallas Temperature.

DallasTemperature sensors(&oneWire);

/***************************************************************************/

void setup(void)

{

 // start serial port

 Serial.begin(9600);
```

```
 Serial.println("Dallas Temperature IC Control Library Demo");
 // Start up the library
 sensors.begin();
}
void loop(void)
{
 // call sensors.requestTemperatures() to issue a global temperature
 // request to all devices on the bus
/********************************************************************/
 Serial.print(" Requesting temperatures...");
 sensors.requestTemperatures(); // Send the command to get temperature readings
 Serial.println("DONE");
/********************************************************************/
 Serial.print("Temperature is: ");
 Serial.print(sensors.getTempCByIndex(0)); // Why "byIndex"?
   // You can have more than one DS18B20 on the same bus.
   // 0 refers to the first IC on the wire
   delay(1000);
}
```

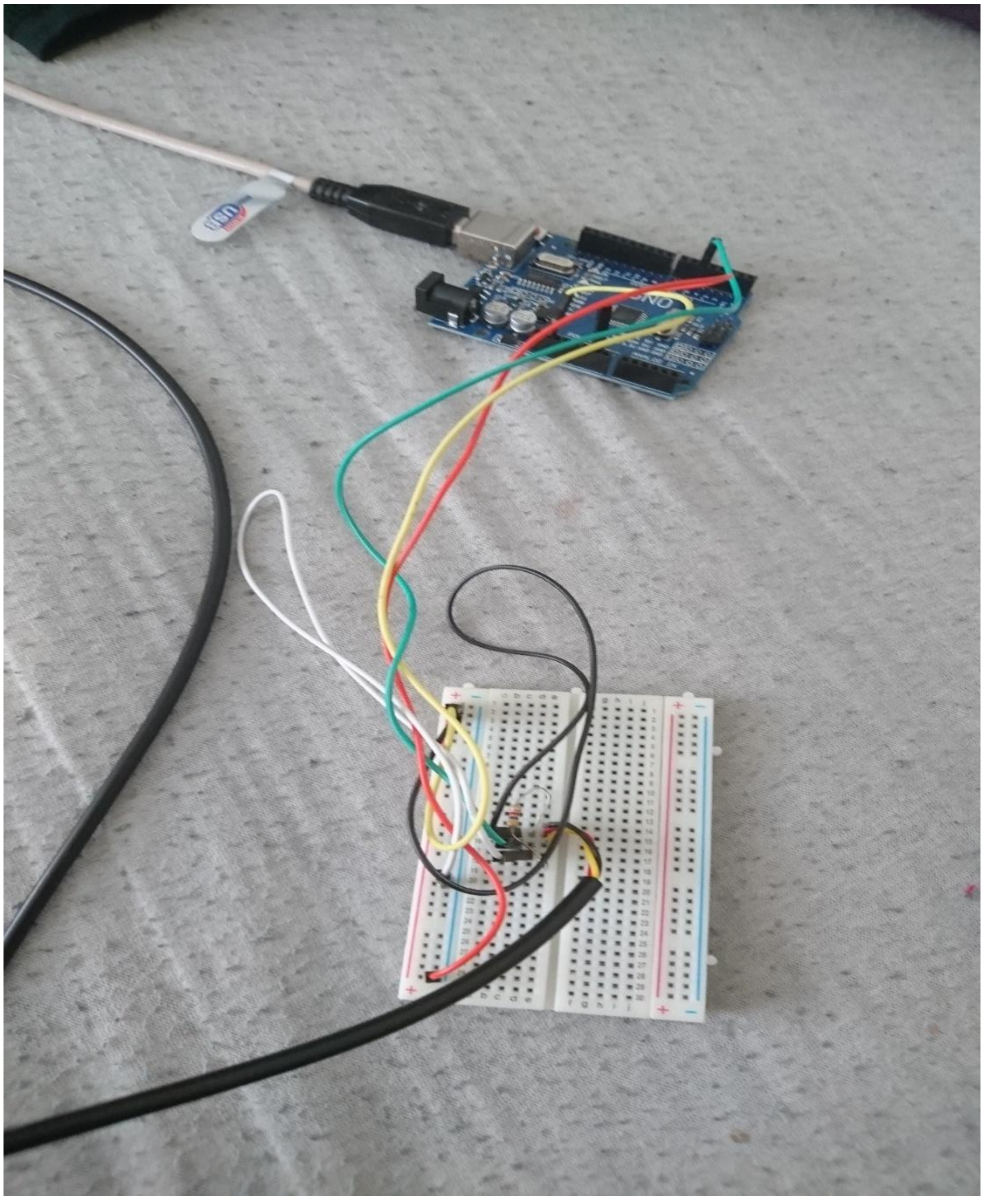
Figure 23. Temperature sensor circuit. Taken by author

4.2 Adjustable wrench and screwdrivers:

The trough was dissembled during the transportation due to the high cost of delivery from the manufacturing place in Cairo to Tallinn. Thus, an Adjustable wrench and screwdrivers were used to put it back together after delivering it to the work place for the experiment.

4.3 Modified parabolic trough

The device consists of six different parts, which are as follows:

Legs. The legs after manufacturing are as shown in Figure 23 below. They were made of compressed carton to decrease the cost of the process and as it is easier to shape and modify.

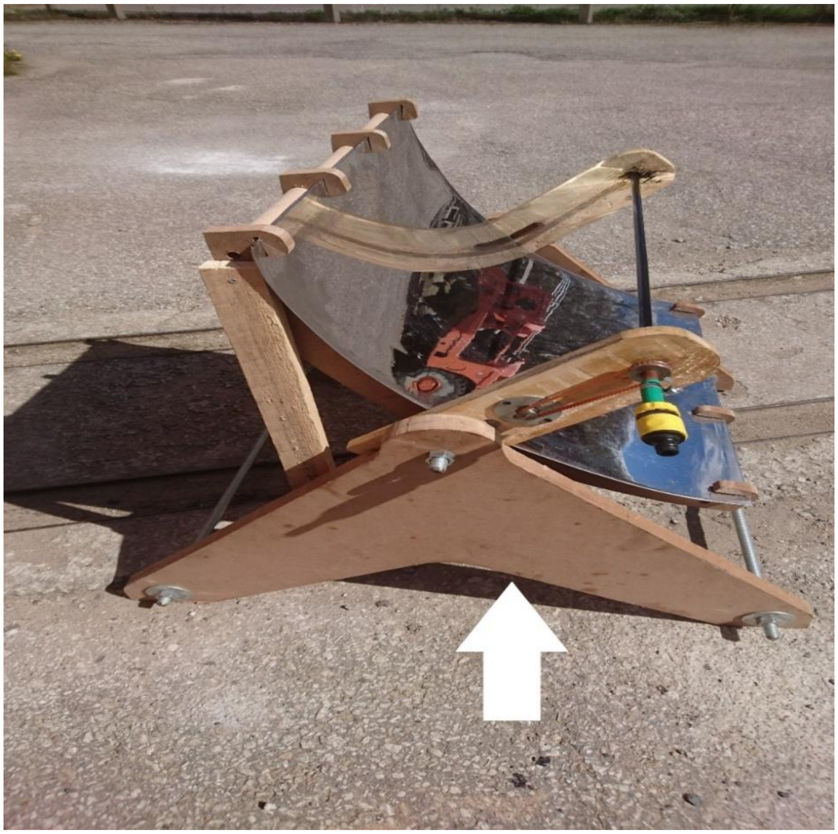

Figure 24. Legs from compressed carton. Taken my author

Black painted copper receiver. The receiver is made of copper, as it is a cheaper option for material selection along with the good heat conductivity properties of copper. The black painting for tube is essential to increase the absorptivity rate of the receiver and to reduce the amount of heat losses. Figure 24 shows the tube after processing and manufacturing process.

Figure 25. Black painted receiver. Taken my author

Arms with electric motor for rotating the receiver. It contains also ball bearings inside to isolate the receiver motion from the arms to avoid friction. This is the main modification in the design of the trough that this project is aiming to test. In the figure below, it shows the connection between the shaft of the motor and a ring around the pipe using a belt. The motor used is 18 Watts and the speed of rotation is controlled using multi voltage power supply.

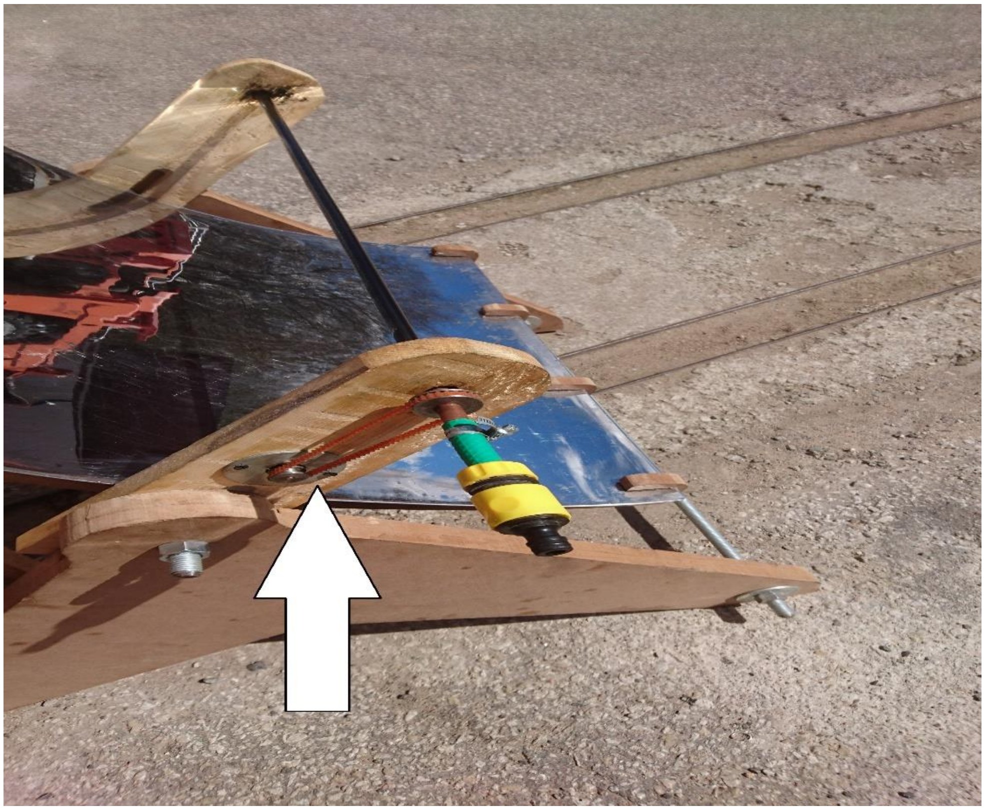

Figure 26. Arms with motor, rings and belt connections. Taken my author

Stainless steel mirror. It was covered with a protective layer during the delivery to protect it from scratches or any damage. The angle of curvature is 90 degrees and all the dimension of the trough was based on this angle such as the length of the arm which hold the receiver. The arms are position is adjustable as well as the mirror, in order to have the receiver at the focal point of the mirrors during testing.

The adjustments is done using the wrench by adjusting the position of the arms in the Elevation direction and then tightening the bolts onto the arms to keep this position. In a standard trough, usually tracking systems are used, and thus this process would be automatic yet this device does not have a tracking system.

Figures 26 and 27 below shows the mirror before removing the protective layer off the mirror and after removing it.

Figure 27. Trough with protective layer. Taken by author.

Figure 28. Trough without protective layer. Taken by author

After the removal of the protective material, the surface of the mirror required cleaning and polishing to remove the remains of the sticky layer of the protective paper. A mixture of liquid Tiner, acidic liquid and soap was used for the process, which took a couple of hours to be completed, which included removal of the layer manually, cleaning the remains, polishing the mirror and drying it.

4.4 Flow rate measurement

The mass flow rate of the thermal fluid is one of the main parameters in the efficiency equation thus I have tested different rates to find the optimum one under which the delta temperature was the maximum. At first, a flow rate meter was used but because it did not fit the diameter of the receiver, so a different method was used. Volume flow rate was measured by measuring the time it took to fill a half litre bottle of water. Then it will be used in the calculations section to calculate the mass flow rate which will be used in the efficiency equation.

5 Methodology

The experimental phase was done on three different parts and each part lasted from 20 to 40 minutes. The three phases are classified as follows:

5.1 Fixed tube

In this phase the trough was tested while the receiver is fixed with rotation and during this phase also the optimum mass flow rate was determined by trying different ones then using the one at which the difference between inlet temperature and outlet temperature was at its maximum. This process was done on the first day before conducting the main experiment upon assembling the device and putting all the parts together. The receiver in the beginning was plain copper then it was painted black upon the very first tests as it should be as per standard parabolic trough design. Before passing the water inside the receiver, its temperature was measured and the atmospheric temperature at this time was 4 degrees Celsius; the receiver temperature went up to 38 degrees which is a really good achievement with all the limitations on this trough that will be mentioned in section 5. This test was done at about 3 pm so the sun radiation was not at its maximum and was in the process of decreasing as the day light fades by approaching the end of the day. The temperature sensor was attached to the inlet of the receiver by making a whole into it and sticking it with wax inside because it was always required to have the readings of the temperature at the inlet constantly. These tests was not used in the main experiment because the main results had to be taken on the same day to make sure that the radiation would not vary much then it would be possible to compare the three phases of the experiment fairly and to have a concrete conclusion. It is necessary to keep the idea that the experiment main focus is not on the overall efficiency of the device in general and this will also be further explained in section 5, however the main point of it, is to study the effect of rotating the receiver and see if it will account for an increase in the delta temperature or not, and if this was the case then it means that the overall efficiency will increase.

5.2 Rotating tube

The first stage of this test is done by rotating the tube at random speeds and then observing the changes in the temperature. Once it is observed that the difference between temperature at the inlet and outlet of the receiver is increasing then it is concluded that the optimum speed of rotation is within the current range of rotation.

This step of the experiment was essential before the next step which is finding the optimum speed in order to check if the idea itself works in general otherwise it would be pointless to continue the experimentation work.

The motor that was used is a simple 18W motor of an old fan. The shaft of the motor is connected to the receiver with a belt and goes around two rings, one over the receiver and the other over the shat of the motor. The speed of rotation was altered by changing the voltage coming to the motor.

5.3 Rotating at different speeds

The final step of the experiment is finding the optimum speed of rotation at which the delta temperature is the maximum. This phase was done over a bigger amount of time in order to allow each change in the speed to take its time to observe the effect on the value of the outlet temperature.

There was some limitations over the rotation of the motor which will be discussed in the discussion section. The section below shows the final results of the readings of the rotation speed against delta temperature and also represented on the chart.

The range of speeds that are displayed on the chart is with really small changes as it was concluded from the tests that higher speeds than the maximum one used in the experiment have a negative effect on the delta temperature.

6. Experimentation and results

6.1 Fixed tube:

The table below shows the results of the experiment by measuring the average delta temperature over several minutes which is a step to calculate first the efficiency of the trough without applying the modification. Readings were taken each second then average per minute was calculated.

Table 6.1.1. Readings of Delta temperature over twenty minutes.

Average delta temperature	Minute
2	1
2	2
2	3
2	4
2	5
2	6
2	7
2.06	8
2	9
2	10
2	11
2	12
1.94	13
-144	14
2	15
1.93	16
1.93	17
1.93	18
1.93	19
1.87	20

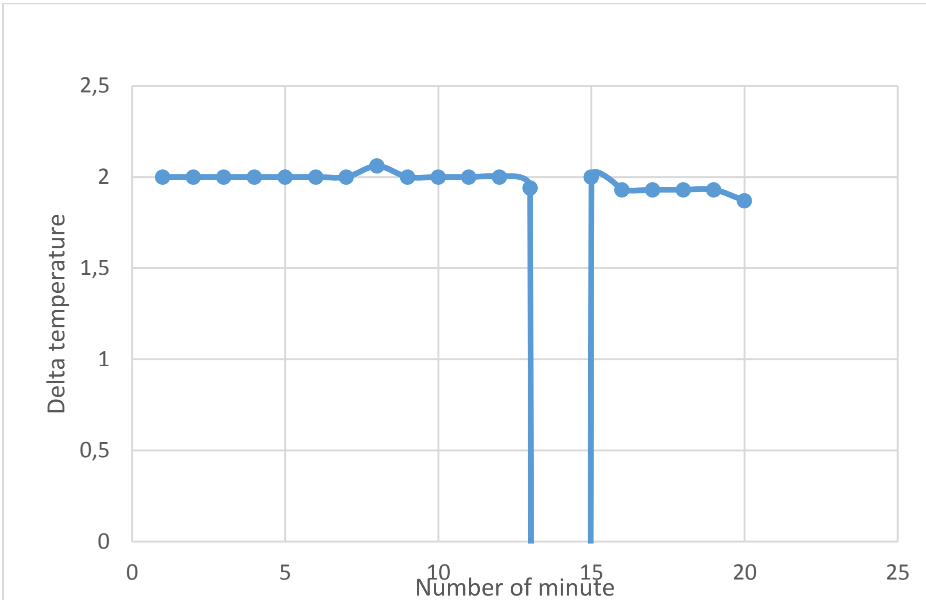

Figure 29. Representation of Fixed tube results.

6.1.1 Comments:

The Arduino controller had an error at one of the readings, which caused a temperature drop as it shows in the table at some point that the delta temperature was -144, so the drop that shows on the chart at one point can be neglected.

6.2 Rotating tube

These are the results of the second phase of the experiment which is done by starting to rotate the receiver at random speeds to see the effect of rotation then trying to find the range within the optimum speed of rotation is located. Readings were taken each second then average per minute was calculated.

Table 6.2.1. The average delta temperature per each minute during the rotation process.

Average Delta temperature	Number of minutes
2	1
2.06	2
2.12	3

2.19	4
2.31	5
2.31	6
2.43	7
2.37	8
2.37	9
2.44	10
2.44	11
2.5	12
2.56	13
2.56	14
2.62	15
2.69	16
2.69	17
2.81	18
2.88	19
2.94	20
3.06	21
3.12	22
3.19	23
3.19	24
3.25	25
3.25	26
3.25	27
3.37	28
3.37	29
3.44	30

The values were taken over 30 minutes to ensure the accuracy of the readings and to allow the sensor to react to the changes. Each sensor has reaction time and a level of sensitivity to the changes of the temperature of the medium it is placed in.

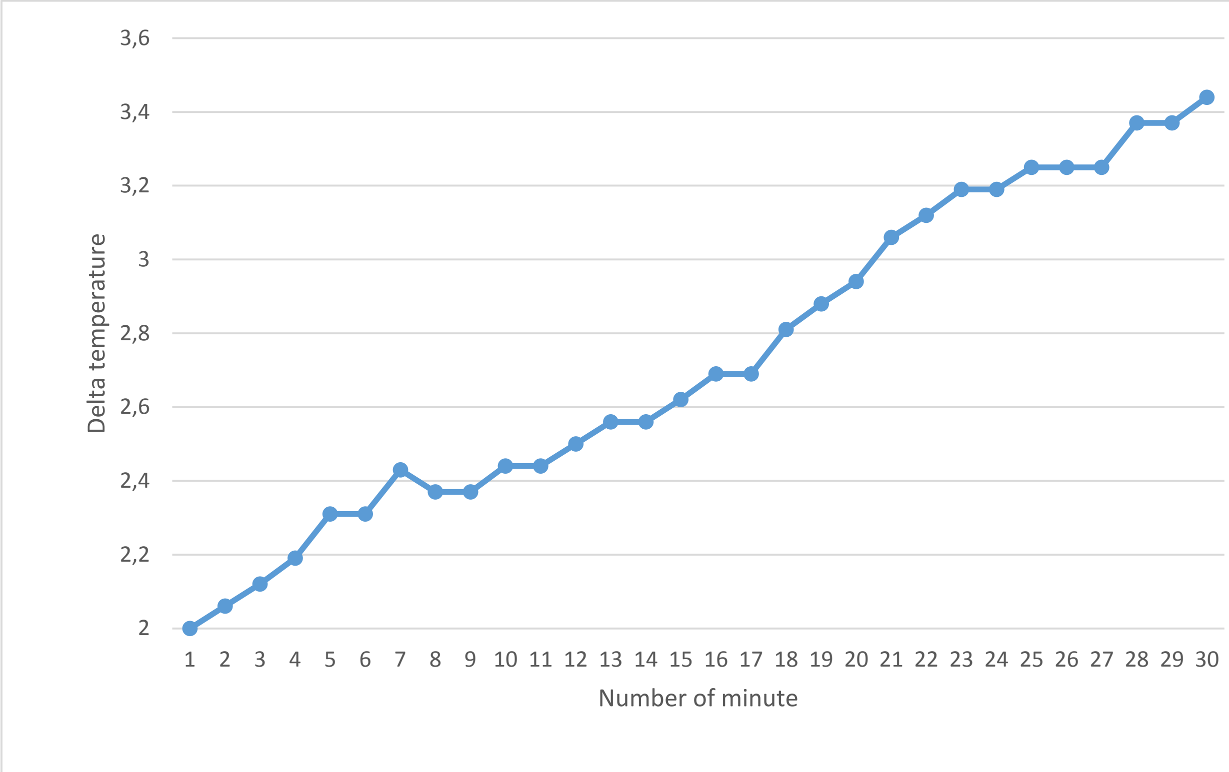

Figure 30. Representation of the results over the chart

6.2.2 Comments:

As the receiver tube started to rotate the average delta temperature started to rise as it shows on the chart which clearly proves that the rotation had a positive effect on the efficiency of the trough.

6.3 Rotating at different speeds:

As the range within which the optimum speed was determined. In this phase, alternating the speeds within this range was applied in order to find the one at which the delta temperature had the maximum value by observing the readings taken each second. It was also recorded per each minute the results of keeping one speed of rotation to avoid false readings.

Table 6.3.1 shows the results of this phase during alternating the speeds

Number of minutes	Average Delta temperature
1	3.56
2	3.62
3	3.68

4	3.75
5	3.81
6	3.93
7	4
8	4.07
9	4.1
10	4.12
11	4.2
12	4.3
13	4.32
14	4.12
15	4
16	3.8
17	3.75
18	3.6
19	3.53
20	3.44
21	3.44
22	3.44
23	3.44
24	3.44

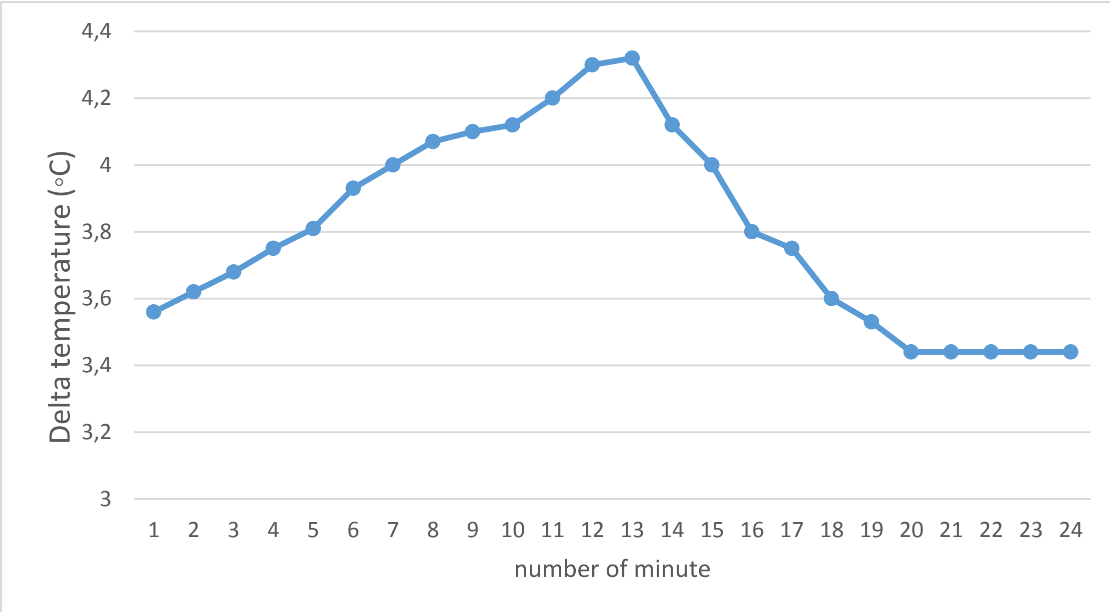

Figure 31. Alternating speeds results per minute

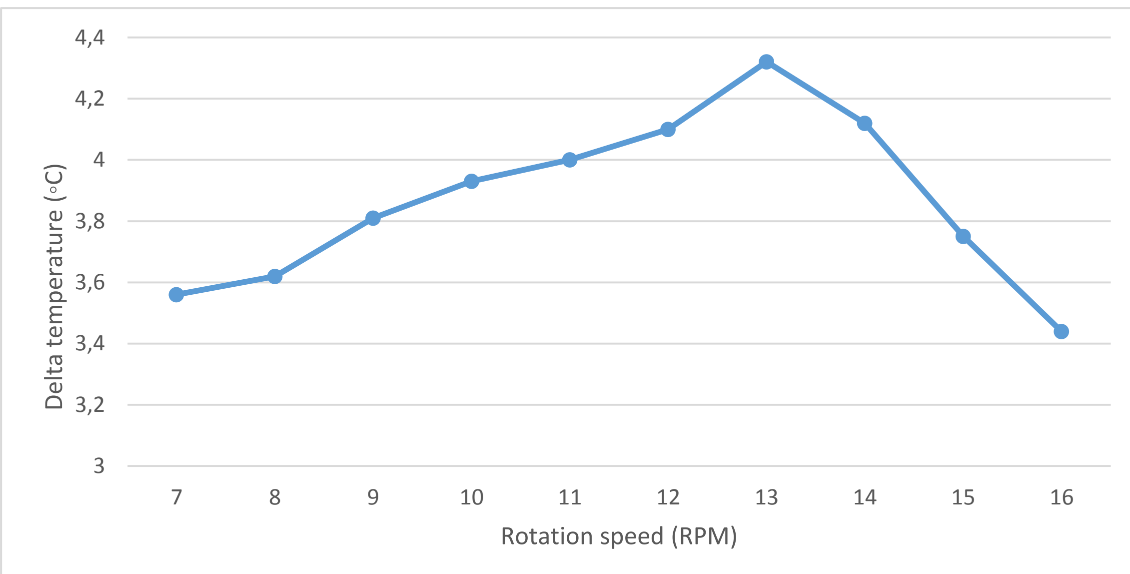

Figure 32. The average delta temperature per each speed of rotation tested.

6.32 comments

The graph shows that the maximum point at which delta temperature had the highest value was at 13 RPM. The speed of rotation varies as the radiation value changes, this is due to the fact that when this experiment was conducted in Cairo, the optimum speed of rotation was different and it was 67 RPM. As the sun radiation in Tallinn is lower than Cairo, thus we can conclude that the speed of rotation will always be lesser as the sun radiation decreases.

7. Calculations

The calculations are simply restricted between getting the thermal efficiency of the trough and the rate of heat transfer in the tube to compare between different cases. The thermal efficiency of a parabolic trough is represented by the following equation:

$$\eta_t = \frac{\dot{m} c_p \Delta T}{AI}$$

Where $\dot{m}$ is the mass flow rate of water in kg/s

C_p is the heat capacity of water in KJ/Kg.K

ΔT is the average temperature in K

A is the area of the tube in m^2

I is the radiation in W/m^2

In the case of a parabolic trough, radiation, conduction and convection occurs, however. It will be as follows:

$$q = IA\Delta T - U_L A\Delta T$$

A is the cross sectional area of receiver in m^2

I is the overall solar radiation available

U_L Is the overall heat transfer coefficient of losses = 7.15 W/m^2 (9)

Due to the fact that the weather stations at the school were not working on the day the experiment was carried out, it was suggested to contact the Estonian weather association for getting the data from them. Unfortunately, they did not provide the data as they did not respond even after calling them directly so the radiation was taken from previous paper study done by the Maailma Meteoroloogiaorganisatsioon in Estonia. According to it, radiation on a day with clear sky is equivalent to 2.5 MJ/m^2 in a measurement taken over 24 hours. Conversion of this value in order to get the radiation in W/m^2 is done as follows:

2.5 MJ/m^2 = 2500000 J/m^2 per hour = 2500000/3600 W/m^2 = 694 W/m^2

Volume flow rate that was used was measured by filling 0.5 L bottle of water, which took 4 minutes and 8 seconds.

Therefore, we can get that $\dot{V} = 0.002\ L/s$

Mass flow rate = Volume flow rate / density

Density of water = 1000 kg/m^3

M = 0.002 * 1000 / 1000 = 0.002 kg/s

7.1 Experiment 1

$$\eta_t = \frac{0.002\ \times 4.187\ \times 1.88}{694.4\ \times (1{,}1 \times\ 10^{-2})^2 \times \pi} = 0.0596 = 5.96\%$$

$$q = 694.4\ \times (1{,}1 \times\ 10^{-2})^2 \times \pi \times 1.88 -\ 7.15\ \times (1{,}1 \times\ 10^{-2})^2\ \times \pi \times 1.88$$
$$= 0.49\ W/m^2 {\circ} C$$

7.2 Experiment 2

$$\eta_t = \frac{0.002\ \times 4.187\ \times 2.72}{694.4\ \times (1{,}1 \times\ 10^{-2})^2 \times \pi} = 0{,}086 = 8.6\ \%$$

$$q = 694.4\ \times (1{,}1 \times\ 10^{-2})^2 \times \pi \times 2.72 -\ 7.15\ \times (1{,}1 \times\ 10^{-2})^2\ \times \pi \times 2.72$$
$$= 0.71\ W/m^2 {\circ} C$$

7.3 Experiment 3

$$\eta_t = \frac{0.002\ \times 4.187\ \times 3.81}{694.4\ \times (1{,}1 \times\ 10^{-2})^2 \times \pi} = 0.12 = 12\ \%$$

$$q = 694.4\ \times (1{,}1 \times\ 10^{-2})^2 \times \pi \times 3.81 -\ 7.15\ \times (1{,}1 \times\ 10^{-2})^2\ \times \pi \times 3.81$$
$$= 0.99\ W/m^2 {\circ} C$$

7.4 Comments

The results clearly shows the difference in the values of the efficiency between the three experiments which clearly shows that the rotation of the tubes had a positive impact on the overall efficiency and rate of heat transfer between the receiver and the water going through it. This was also clear in the results section by observing the differences between the three experiments in temperature readings. As per the results of efficiency of the device when the receiver was fixed the value was 5.96% and after rotating the receiver on optimum rotational speed it was 12% so we can conclude that the modification doubled the overall efficiency of the trough.

Considering all the limitations and the quality of the device used for testing, this indicates that the impact of the modification was highly positive on the overall performance. This experiment was also done in Cairo and same results were achieved. This was for the purpose to experiment the modification in area with higher radiation and ambient temperature. The limitations on the device that caused the values of the efficiencies to be lower than normal are explained in the next section.

8. Discussion

8.1 Receiver design:

Many limitations in the design of the device did affect the results and had impact on its overall efficiency. It was intended to do the experiment on a properly manufactured device with machines not a hand made one yet unfortunately, all companies selling parabolic troughs only take whole sale orders for the purpose of building an actual power plant so it was not possible to get a single parabolic trough for the purpose of testing. The most complicated part in the process of the design of a parabolic trough is the receiver part. It requires specific materials for painting it and adding special coating to increase its absorption rate. In addition, a glass cover is required around the tube to isolate it from atmospheric temperature and the space inside this coating is vacuum to prevent heat losses through conduction, convection and radiation. The figure below, shows the actual receiver part of parabolic troughs sold on the market

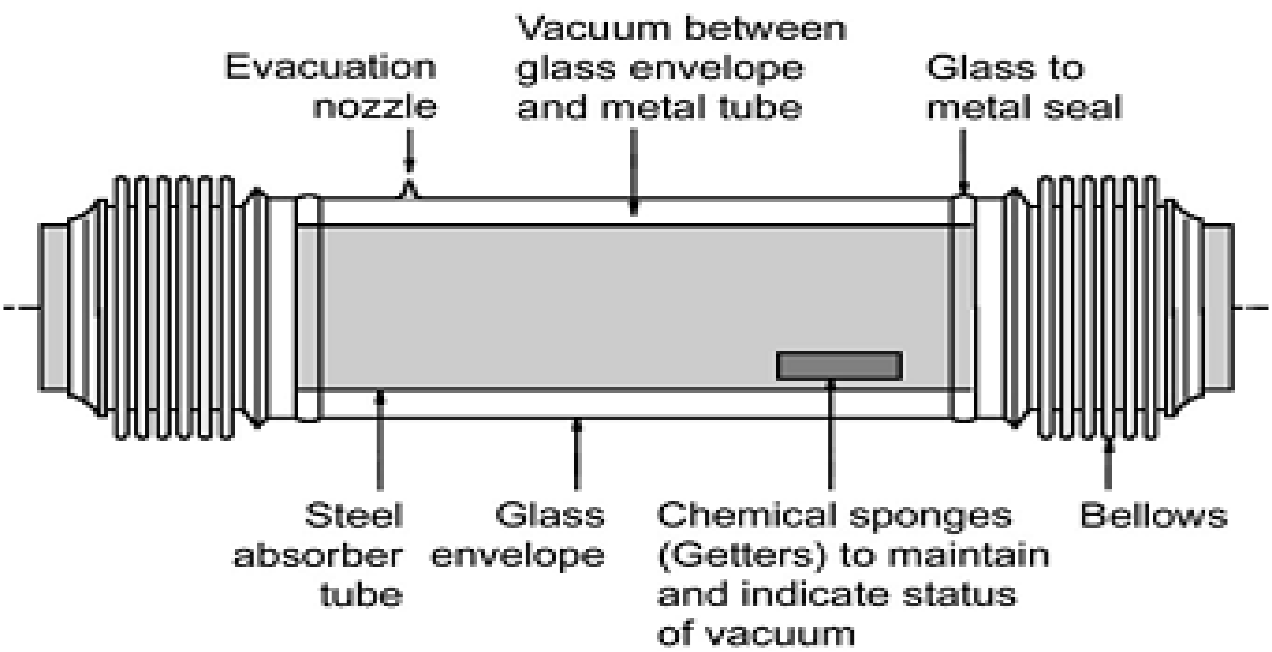

Figure 33. Receiver design of a standard parabolic trough (19)

These factors were missing in the trough that was used for the experiment, which affected its overall efficiency drastically, however the main purpose of the experiment was to study the effect of rotating the tube and if it will have impact on the difference between the temperature at the inlet and the outlet of the receiver which was clearly shown in the results so the new idea applied to the device to improve its overall efficiency did work.

It can be seen clearly in the figure below for the device that was used for the experiment how the receiver part was different from a normal one in a properly manufactured trough.

Figure 34. Receiver of designed trough without glass coating for isolation. Taken by author

7.2 Mirror design:

A second factor that also affected the overall efficiency is the focal point of the parabola. The calculations were made in the design part to have the receiver exactly on the focal point where all the incoming sun rays are reflected by the parabola and focused, yet as the device is not accurately manufactured, there is a significant error at this part.

In a normal manufacturing process, the sheet metal is entered in a CNC machine for bending it to the specified angle and the length of the arms holding the receiver is calculated based on this. After this part is finished, further tests are made to make sure that the receiver is exactly on the focal point of the mirror.

The figure below shows how the ray's reflection should be perfectly aligned on the receiver in a parabolic trough.

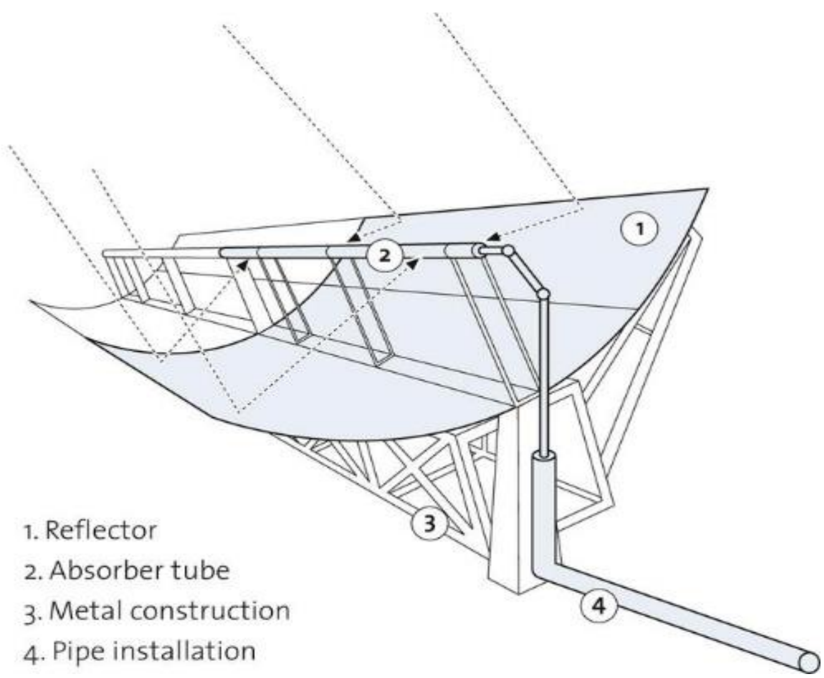

Figure 35. Reflection of incident rays on the receiver in a standard trough. Designed by author

In order to accomplish this, as mentioned above, factories use specific machines for manufacturing, material processing and testing equipment to make sure that the alignment of the focal point on the tube was reached.

7.2 Efficiency of a power plant:

Normally, a steam power plant that uses parabolic troughs for pre-heating process before the water enters the combustion chamber contains hundreds of troughs aligned together as the temperature of the water rises as it passes through each receiver. Thus, the effect of one trough over the temperature of water or any thermal fluid being passed through the receiver does not really account for the overall outcome or advantage of this pre-heating stage, yet it is the effect of all the troughs being used in parallel.

For example, If we have steam power plant with pre heating stage using a 100 parabolic trough and each trough heats up the water by 4 degrees, this means that the water temperature will go up to 400 degrees before entering the combustion chamber of the plant for burning the fuel to make the water reach the super-heated vapour stage for running the turbine and produce electricity.

7.3 Issues with the Motor

The motor that was used for rotating the receiver had unexpectedly higher torque than required so it was really hard to make it work on lower speeds. Thus, it was tested until the lowest speed possible to be achieved from it yet the range within which the optimum speed of rotation is found was not detected.

Due to this incident, the receiver was rotated manually and steadily to get such speeds, it was possible to achieve this as the optimum speed of rotation was really low as shown in the results section. The motor can be easily replaced from the body of the trough with another suitable one yet due to limitations on time and budget, it was decided to proceed that way.

8. Conclusion

To sum up, the overall result of the idea can be considered a success due to its simplicity, low cost of applying and the effect on the overall efficiency of a parabolic trough.

The points mentioned in the discussion part can be used in case of further testing to be applied to have more reliable results and improve the overall accuracy of the experiment. Although there were many factors that limited the overall efficiency as well as making use of the full potential of the sun radiation available, the fact that the newly added modification was able to improve the device performance is the main target of this whole project which what was achieved. There can be other applications or heating processes that this idea can be applicable for such as glass manufacturing, oil refining and desalination of water.

In addition, one other factor that enhances the idea of the project and encourage for applying it, is the cost. Due to the fact that no high speeds of rotation is required along with the ease of applying the design even to already manufactured troughs. This is why the cost analysis was not taken into consideration in the calculations. The electricity consumption of the motor used to rotate the receiver is also negligible if compared to the overall work output and impact on saving fuel in case of a steam power plant.

It is commonly known that all renewable energy production devices are environmentally friendly; this is also an additional factor that adds to the value of the modification and that is the fact that it keeps this identity if used as there are no emissions or waste produced. As the device was tested in Estonia then it is also essential to mention the potential of solar energy in it. If we take into consideration that the solar photovoltaic energy efficiency potential in Estonia is 100 kWh/m2 and covering 20% of the total roof area of dwellings in Estonia, we get that the solar photovoltaic power potential in Estonia will be about 0.7 TWh. Since solar energy was not yet explored much in Estonia, and the lack of economical resource, a gradual development is expected. (2)

It is just matter of time until solar energy potential in Estonia is fully used. This is an inevitable future occurrence as the European Union energy strategy and future plans fully targets increasing the dependence on renewable energy resources to decrease the amount of emissions and global warming effects and limit the dependence on non-renewable ones which is considered as a one of the biggest challenges we are facing nowadays.

Curriculum Vitae

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Education:

Current : Masters of materials and processes of sustainable energetics in Tallinn university of technology

2008 - 2013 : Bachelor in the field of mechanical engineering from Loughborough university

2005 - 2008 : International general certificate in secondary education (I.G.C.S.E) Cambridge and London examination boards

Trainings and internships:

2016 (1 week) : Emerlad forest Business Marketing Simulation, winner of first place with highest net profit

2015 (2 months) : Sales agent for Kakslautten hotel in Finland

2012 (2 months) : Internship in the university of Nevada Las Vegas in the field of solar and renewable energy

2011 (2 months) : Training in the field of control engineering in Giza Systems company with the topics of PLCs, DCS, Optical Fibers, PIDs and Optical Fibers

2010 (2 months) : Theoretical Training in the field of control engineering in Giza Systems company with the topics of PLCs, DCS, Optical Fibers, PIDs and Optical Fibers

2010 (1month) : Training in Vodafone in the field of Human Resources and organizational techniques

2010 (1month) : Training in the field of presentation and communication skills

Work Experience:

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Jan. 2012 - Jan. 2013 : Sales manager in "Pull and Bear"

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