Thermal Analysis, Design and Experimental Investigation of Parabolic Trough Solar Collector

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Abstract. Energy is one of the building blocks of modern society. Solar energy is a form of renewable energy which is available abundantly and collected unreservedly. In this paper, the application of solar energy using parabolic trough is analyzed. An experimental setup was developed to investigate the performance of the parabolic trough. Measurements of total direct radiation on the plane of the collector, ambient temperature, wind speed, water flow rate, and inlet and outlet temperatures of the water inside the absorber tube were measured and employed in studying the performance of the parabolic trough. A data logger and a computer were employed for data acquisition and the outputs of the experiment are illustrated with the help of graphs plotted using the data import-wizard data import-wizard of the data logger and MATLAB software. Finally, the efficiency which is used as a measure of performance is calculated and the experimental results are compared with the results obtained from the mathematical model.

Keywords: Thermal Analysis, Parabolic Trough, Solar Collector, Experimental Investigation, Solar Energy.

1 Introduction

Energy is one of the crucial inputs for socio-economic development. The rate at which energy is being consumed by a nation often reflects the level of prosperity that it could achieve. The total energy consumption increases with economic and population growth and, at the same time, various environmental problems associated with human activities become increasingly serious.

In addition to an increase in price of fossil fuel products, resources will be exhausted in a relatively short period of time. The current high price of fossil fuel resources is affecting economic and social development worldwide. The impact of energy crises is particularly felt in less developed countries where a high percentage of national budgets for development must be diverted to the purchase of fossil fuel products. To reduce the dependency on imported fuels with high price, most countries

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have initiated programs to develop alternative energy sources based on domestic renewable resources. In order to achieve the goals of sustainable development, it is essential to minimize the consumption of finite natural resources and to mitigate the environmental burden to within nature's restorative capacity.

There is now a global consensus that the new sources of energy have to be renewable to satisfy the global energy demand in the long term. Solar thermal power plants are one of the most promising options for renewable electric power production. Unlike traditional power plants, concentrating solar power systems provide an environmentally friendly source of energy, producing virtually no emissions and consuming no fuel other than sunlight.

Ethiopia is one of the countries which is found around the equator in which a better solar radiation exists that creates favorable conditions for the exploitation of solar energy. This can make parabolic trough solar power generation system optional for power production in the country.

2 Statement of the Problem

Ethiopia, in addition to the persistent food insecurity, is suffering from energy supply. It is observed through studies and recent data, energy consumption increases proportionally to the gross national product. One of the possible methods of overcoming energy crisis is by increasing the use of freely available renewable energy sources such as solar energy.

Because of the proximity to the equator, Ethiopia receives adequate sunshine throughout the year. The annual average daily radiation in Ethiopia reaching the ground is about 5.2kWh/m^2/day. The minimum annual average radiation for the country as a whole is estimated to be 4.5 kWh/m^2/day in July to a maximum of 5.55 kWh/m^2/day in February and March [1].

Many industries in the country use fuel for water heating process. However, energy costs for heating water is increasing at considerable rate by increasing operating costs and reducing profitability due to continuous escalating of fuel price. Hence, this research explores solar energy as a sustainable alternative for large scale water heating and power generation and it is a step forward to reduce dependency on imported oils.

3 Significance of the Research

Energy is one of the current issues of the country. There is a large energy demand in the country and to fulfill this demand the government is working on different sources of energy.

The result from the study explores solar energy as a sustainable alternative for large scale water heating and power generation and it is a step forward to reduce dependency on imported oils.

The study benefits different industries in reducing the cost related to fuel and other high cost energy sources. This in turn develops the energy alternatives for the industry as well as the country. In addition, this research can be used as a reference for further study in the area.

4 Solar Energy

Solar radiation, often called the solar resource, is a general term for the electromagnetic radiation emitted by the sun. Solar radiation can be captured and turned into useful forms of energy such as heat and electricity, using a variety of technologies. However, the technical feasibility and economical operation of these technologies at a specific location depend on the available solar resource.

From the rays of the sun, which pass through the earth's atmosphere to the ground, a portion is scattered by particles or clouds. The intensity of solar radiation outside the atmosphere is about 1.3 kW/m^2. Even though only a fraction of this actually hits the earth's surface, the magnitude of the energy from this source is enormous. For example, utilizing only 1% of the earth's deserts and applying a conversion efficiency of 15% to produce electric energy would develop more electricity than is currently produced worldwide by fossil fuels [3]. This is not practical given the need to distribute the electricity to users around the world, but it does highlight the magnitude of this resource.

Global radiation is radiation energy incident on a surface, which is comprised of a diffuse (scattered) component and a direct normal component (the part coming undisturbed directly from the sun). Figure 1 illustrates the definitions of global, diffuse and Direct Normal Radiation (DNR).

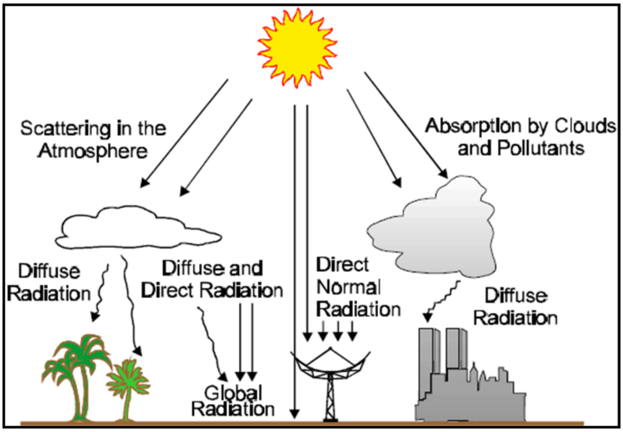

Fig. 1. Direct normal, diffuse and global radiation [3]

The main components of a CSP system are:

4.1 Integration of Parabolic Troughs with Other Energy Systems

As discussed earlier, the Solar Electric Generating System (SEGS) is fundamentally a steam turbine power plant in which the main fuel is solar radiation. Figure 2 shows a schematic diagram of a typical plant configuration [3].

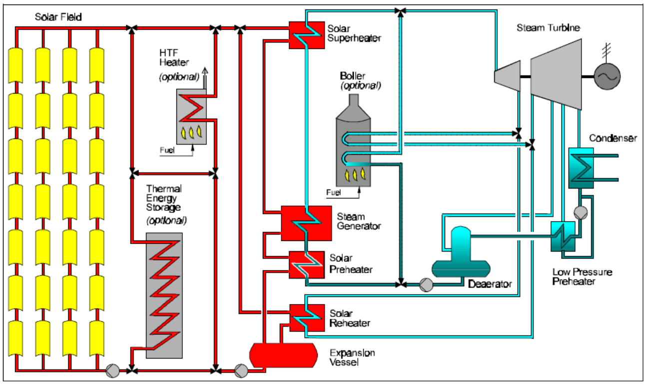

Fig. 2. Parabolic troughs integrated with steam power plants [12]

5 Mathematical Modeling of the Parabolic Trough

In analyzing the solar parabolic collector, it is important to identify each and every part of the collector and the terms used on the solar collector.

In the concept and design of the parabolic collector, the first definition is strictly geometric as ratio of aperture area to receiver area. The ratio of these two areas defines the concentration ratio of the parabolic trough as [24]:

$$C = \frac{A_a}{A_r} \quad , \quad A_a = W_a \times L, \quad A_r = \pi DL \tag{1}$$

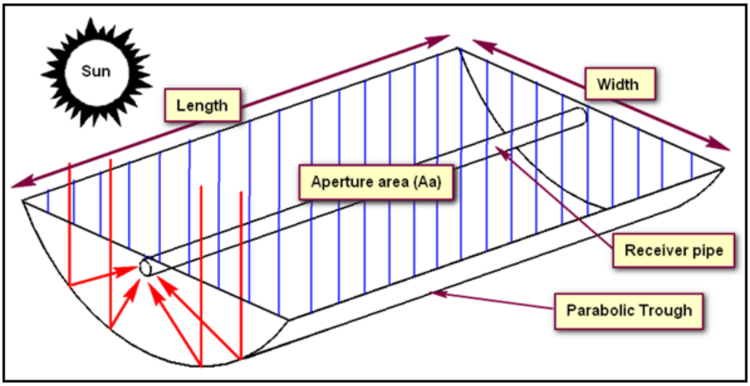

Fig. 3. Parabolic trough

5.1 Heat Collecting Element (HCE) Performance Model

The HCE performance model is based on an energy balance on the collector and the HCE. The energy balance includes the direct normal solar irradiation incident on the collector, optical losses from both the collector and HCE, thermal losses from the HCE and the heat gained by the HTF. Temperature gradient on the receiver can be accounted for by a flow factor FR to allow the use of inlet fluid temperature in energy balance equation. Thus, it is required to drive appropriate expressions for the collector efficiency factor F', the loss coefficient UL and the heat removal factor FR to numerically evaluate the outlet temperature. All the equations and relationships used in one-dimensional HCE performance models are described in the following sections.

5.2 One-Dimensional Energy Balance Model

The HCE performance model uses an energy balance between the HTF and the atmosphere, and includes all equations and correlations necessary to predict the terms in the energy balance, which depend on the collector type, HCE condition, optical properties and ambient conditions.

Figure 4 shows the one-dimensional steady-state energy balance for a cross-section of an HCE and Figure 8 shows the thermal resistance model and subscript definitions. For clarity, the incoming solar energy and optical losses have been omitted from the resistance model. The optical losses are due to imperfections in the collector mirrors, tracking errors, shading and mirror and HCE cleanliness. The effective incoming solar energy (solar energy minus optical losses) is absorbed by the selective coating ($\dot{q}'_{3\,SolAbs}$). Some of the energy that is absorbed by the selective coating is conducted through the absorber ($\dot{q}'_{23\,SolAbs}$) and transferred to the HTF by convection ($\dot{q}'_{12\,Conv}$); the remaining energy is transmitted back to the environment by convection ($\dot{q}'_{35\,Conv}$) and radiation ($\dot{q}'_{34\,rad}$).

Table 1. Heat flux definitions

Heat Flux Heat Transfer Path [W/m]	Heat Transfer Mode and Transfer Path
$\dot{q}'_{3SolAbs}$	Solar irradiation absorption from incident solar irradiation to outer absorber pipe surface
$\dot{q}'_{23Cond}$	Conduction heat flux from outer absorber pipe surface to inner absorber pipe surface
$\dot{q}'_{12Conv}$	Convection heat flux from inner absorber pipe surface to heat transfer fluid.
$\dot{q}'_{35Conv}$	Convection heat from outer absorber pipe surface to ambient
$\dot{q}'_{34rad}$	Heat radiation from outer absorber pipe surface to sky

The model assumes all temperatures, heat fluxes, and thermodynamic properties are uniform around the circumference of the HCE. All heat flux directions shown in Figure 7 are positive and all terms indicated in the above paragraph are defined in Table 1. Dotted variables indicate rates and the prime indicates per unit length of receiver and a double prime indicates per unit normal aperture area.

The energy balance equations are determined by conserving energy for each surface of the HCE cross section, referencing Figure 4.

$$\dot{q}'_{12conv} = \dot{q}'_{23cond} \tag{2}$$

$$\dot{q}'_{3SolAbs} = \dot{q}'_{23Cond} + \dot{q}'_{35Conv} + \dot{q}'_{34rad} \tag{3}$$

$$\dot{q}'_{HeatLoss} = \dot{q}'_{35Conv} + \dot{q}'_{34rad} \tag{4}$$

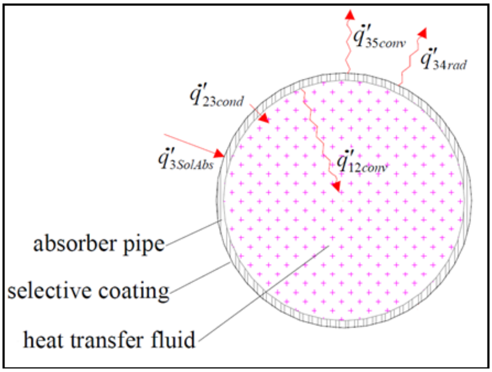

Fig. 4. One-dimensional steady-state energy balance

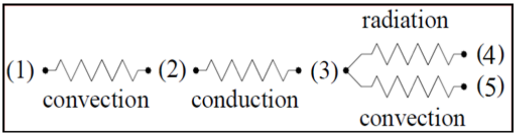

Fig. 5. Thermal resistance model for a cross-section of an HCE

In Figure 5, Point 1 is heat transfer fluid, Point 2 is absorber inner surface, Point 3 is absorber outer surface, Point 4 is sky and Point 5 is surrounding air.

5.3 Convection Heat Transfer between the HTF and the Absorber

From Newton's law of cooling, the convection heat transfer from the inside surface of the absorber pipe to the HTF is:

$$\dot{q}'_{12Conv} = h_1 D_1 \pi (T_2 - T_1) \quad (\mathrm{W/m})$$

$$h_1 = Nu_{D1} \frac{k_1}{D_1} \tag{5}$$

In these equations, both T1 and T2 are independent of angular and longitudinal HCE directions, as will be all temperatures and properties in the one-dimensional energy balance model.

5.4 Conduction Heat Transfer through the Absorber Wall

Fourier's law of conduction through a hollow cylinder describes the conduction heat transfer through the absorber wall [26].

$$\dot{q}'_{23Cond} = 2\pi k_{23}(T_2 - T_3) / \ln(D_2 / D_1)(W / m) \tag{6}$$

In this equation, the conduction heat transfer coefficient is constant and is evaluated at the average temperature between the inner and outer surfaces.

5.5 Heat Transfer from the Absorber Wall to the Atmosphere

The heat will transfer from the glass envelope to the atmosphere by convection and radiation. The convection will either be forced or natural, depending on whether there is wind. Radiation heat loss occurs due to the temperature difference between the glass envelope and sky.

Convection Heat Transfer

The convection heat transfer from the glass envelope to the atmosphere (q''_{35Conv}) is the largest source of heat loss, especially if there is wind. From Newton's law of cooling

$$\dot{q}'_{35Conv} = h_{35} D_2 \pi (T_3 - T_5) \quad (\mathrm{W/m})$$

$$h_{35} = Nu_{D2} \frac{k_3}{D_2} \tag{7}$$

The Nusselt number depends on whether the convection heat transfer is natural or forced (i.e no wind or with wind). Since the experimental setup is in the open field, the convection heat transfer is assumed to be forced (with wind).

Radiation Heat Transfer

The useful incoming solar irradiation is included in the solar absorption terms. Therefore, the radiation transfer between the outer surface of the tube and sky is caused by the temperature difference between the outer surface of the tube and the sky. To approximate this, the outer surface of the tube is assumed to be a small convex gray object in a large blackbody cavity (sky). The net radiation transfer between the glass envelope and sky becomes [26].

$$\dot{q}'_{34rad} = \sigma\pi D_2 \varepsilon_3 \left(T_3^{\,4} - T_4^{\,4}\right) \text{(W/m)} \tag{8}$$

5.6 Solar Irradiation Absorption

Using basic energy balance equation, the useful energy gained per unit collector length expressed in terms of the local receiver tube temperature and the absorbed solar radiation per unit of the aperture area, which is the difference between the absorbed solar radiation and the thermal loss and is given by:

$$\dot{q}'_{used} = \frac{A_a \dot{q}_{ab} - A_t U_L (T_t - T_a)}{L} \tag{9}$$

$$\dot{q}_{ab} = \alpha_O I_t \tag{10}$$

$$A_t = \pi D_2 L \tag{11}$$

In terms of the energy transferred in to the working fluid at local fluid temperature:

$$\dot{q}'_{used} = \frac{\left(\frac{A_t}{L}\right)(T_t - T_f)}{\frac{D_2}{h_1 D_1} + \frac{D_2}{2k}\ln\left(\frac{D_2}{D_1}\right)} \tag{12}$$

Rewriting Equation 7 in the form of Tt and substituting in Equation 10, the following equation is obtained:

$$\dot{q}'_{used} = F' \frac{A_a}{L}\left[\dot{q}_{ab} - \frac{A_t}{A_a} U_L (T_f - T_a)\right] \tag{13}$$

F' is collector efficiency factor which is given by:

$$F' = \frac{\frac{1}{U_L}}{\frac{1}{U_L} + \frac{D_2}{h_1 D_1} + \frac{D_2}{2k}\ln\left(\frac{D_2}{D_1}\right)} \tag{14}$$

This can be rewritten in the form of:

$$F' = \frac{U_O}{U_L} \tag{15}$$

The actual useful energy collected by fluid is, therefore, given by:

$$\dot{q}'_{used} = F_R \left[\frac{A_a \dot{q}_{ab} - A_t U_L (T_{fi} - T_a)}{L}\right] \tag{16}$$

Where F_R is the collector heat removal factor, defined as the ratio of the actual useful energy gain to the useful energy gain, if the entire collector was at the fluid inlet temperature T_{fi} and it is expressed as:

$$F_R = \frac{\dot{m}C_{pf}(T_{fo} - T_{fi})}{\frac{A_a}{L}\left[\dot{q}_{ab} - \frac{A_t}{A_a}U_L(T_{fi} - T_a)\right]} \tag{17}$$

After rearranging the above equation, including the collector efficiency factor, it becomes:

$$F_R = \frac{\dot{m}C_{pf}}{A_t U_L}\left[1 - \exp\left(-\frac{A_t U_L F'}{\dot{m}_f C_{pf}}\right)\right] \tag{18}$$

Finally, rearranging the above equations in the form of T_{fo}, then the exit temperature of the water from the heat collecting tube can be calculated from the following equation:

$$T_{fo} = T_{fi} + \frac{\dot{q}'_{used}}{\dot{m}_f C_{pf}} \tag{19}$$

6 Setup of Experimental Components

6.1 Parabolic Trough Stand

The stand, four legged, holds all the components: the parabolic trough support, the ratchet mechanism and tracing mechanism, up right from the floor. It has three parts: the lower part of the stand is connected to the concrete foundation using anchoring bolts. The stand is linked to the upper part of the trough by a mechanism that allows 360^O (the actual angle of rotation need to trace the sun's position 47.3^0) rotation of the trough to trace the sun's monthly position.

Fig. 6. Stand of the parabolic trough

6.2 Trough Support

This part of the parabolic trough connects the lower part of the support to the upper part of the trough. The parabolic troughs are connected to this support using bearings so that it is free to rotate from east to west to trace the solar position. This part also gives a rigid structural support of the trough with the stand. The connection between the stand and trough support is contact connection to let the trough support rotate through 360^0 over the stand.

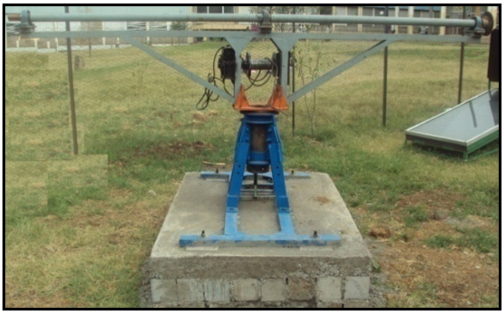

Fig. 7. Trough support

6.3 The Parabolic Trough

The parabolic trough is the most important part of the assembly. The solar radiation strikes the surface of the trough and is reflected to the focal point. The parabolic trough structure is made from RHS metal and angle iron and the reflecting material is aluminum sheet.

Fig. 8. The parabolic trough

6.4 Heat Exchanger

The heat exchanger is one of the components of this experimental setup. After the working fluid is heated by the solar radiation, the heat should be rejected at some point in the experiment setup because the working fluid will circulate again through the collector tube. The heat exchanger that is used for this purpose is shell and tube heat exchanger.

Fig. 9. Heat exchanger

6.5 HTF Pump

The pump is the driving force to circulate the HTF in this experimental setup. The selection of the pump is done considering the layout of the setup, the total pressure loss and the availability of the pump in the market.

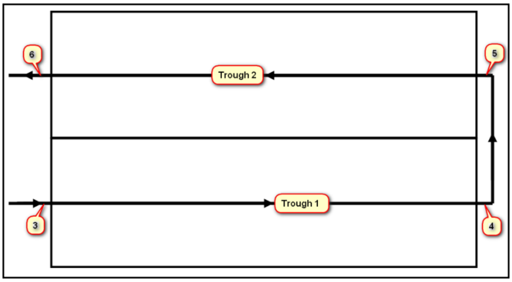

Fig. 10. Top view of the experimental setup layout

Where: 3-Inlet point of the first trough, 4-outlet of first tough, 5-inlet of second trough and 6-outlet of second trough.

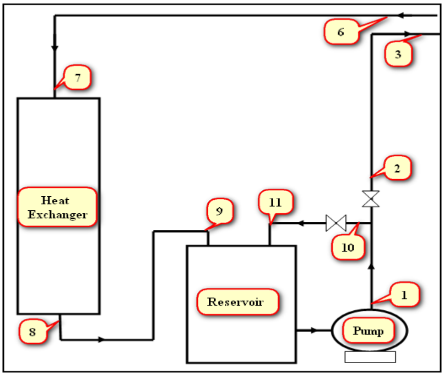

Fig. 11. Front view of the experimental setup layout

Where: 1-outlet of pump, 2-outlet of first flow controlling valve, 7-inlet of Heat exchanger, 8-exit of heat exchanger, 9-inlet of reservoir, 11-outlet of second flow controlling valve.

The parabolic trough is designed to track the sun in any direction. There are two rotational axes to make the tracking system easy. The first rotational axis allows the trough to track the sun from east to west during the day and the second rotational axis allows the trough to rotate in the vertical rotational axis to track the seasonal sun direction change from east to northeast and east to southeast.

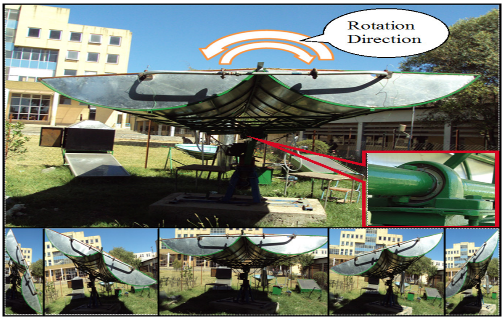

Fig. 12. Rotational directions from east to west

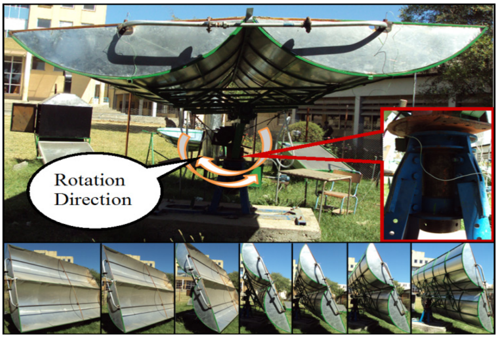

Fig. 13. Rotational Direction with vertical rotational axis

7 Results

In this section, the thermal performance of parabolic trough solar collector is investigated using the measured data of the inlet and outlet temperatures of the working fluid, ambient temperature, wind speed and global radiation around the experimental setup. Plots of the performance parameters are also done using MATLAB software from the data logger import wizard to Microsoft excel worksheet.

Generally, in the test setup, water is circulated through the absorber tube, then to the heat exchanger, finally to the reservoir and again it is pumped back to the absorber tube. A regulating mechanism which is a gate valve is used to alter the flow rate in the system. Temperature of water incoming into and outgoing from the absorber tube are logged using data acquisition system. The pump circulates the water throughout the day starting from sunrise up to sunset. This is in line with the general test procedure in all standards.

The ambient temperature variation in the vicinity of the trough during the day is shown in Figure 16.

The test was started at 8:40 in the morning and ended 16:30 in the afternoon. The maximum temperature measured was 22.99^{0}C between 14:15 and 15:03 in the afternoon and the minimum temperature measured was 17.9 ^{0}C at 8:40 in the morning.

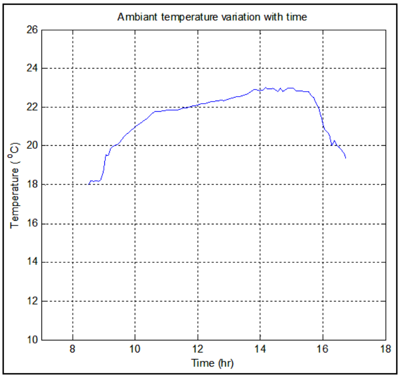

Fig. 14. Variation of ambient temperature

The direct solar radiation variation is shown in Figure 17. The maximum radiation measured was 1049.519W/m2 and the minimum value 302.32 W/m2.

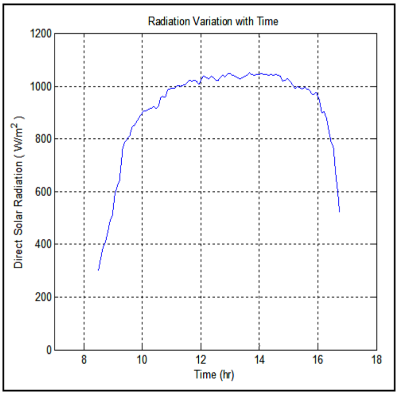

Fig. 15. Variation of Direct Solar Radiation

The temperature variations of the two troughs are shown in Figure 18. The first trough increased the water temperature to a maximum of 55.95^{0}C, which remained above 55^{0}C for two working hours, starting from 12:15 up to 14:23, and above 50^{0}C for five and a half working hours starting from 10:17 up to 15:42. The second trough increased the water temperature to a maximum of 73^{0}C, raising the temperature above 70^{0}C for about five working hours starting from 10:42 up to 14:30.

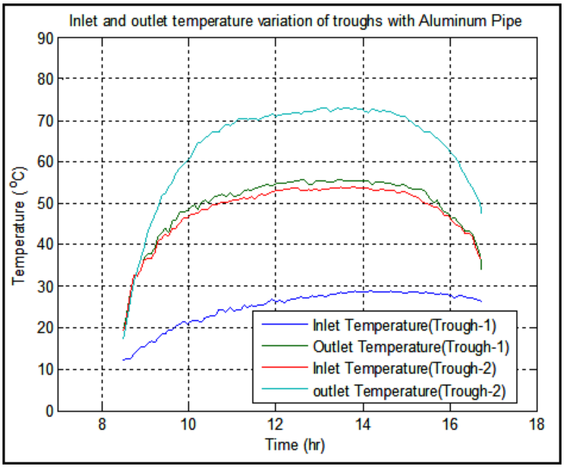

Fig. 16. Inlet and Outlet Temperature Variation of the water

The efficiency of the aluminum heat collector pipe fluctuates between 50% - 60% starting from 10:00 up to 16:00, more than six working hours.

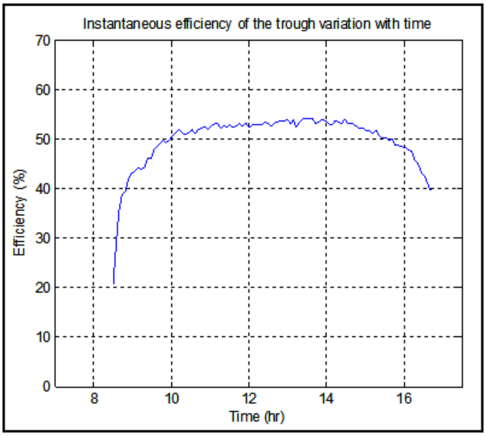

Fig. 17. Instantaneous efficiency of the aluminum heat collecting pipe

The test results are also compared with the mathematical model analysis. From graphs shown in Figure 20, the temperature difference between the analytical model and the actual test results are seen to lie between 0 and 10^0C. These deviations can be accounted for by the manufacturing and test procedures errors.

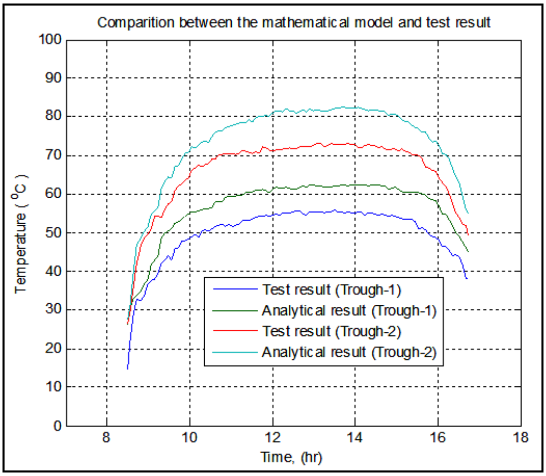

Fig. 18. Comparisons between the mathematical model and test result

8 Conclusion

The major aim of this project work was to design, manufacture and conduct an experimental investigation on the performance of parabolic trough and prepare a mathematical model to verify the results obtained during the test period

This paper has attempted to highlight the following issues

- Based on the current status of the country a new method of a solar energy application has been tested and new technical and technological opportunities of a solar energy application in water heating and steam generation has been established.
- Aluminum sheet material bends easily into the required parabolic trough shape. Black painted aluminum pipe is used as absorber tube. Temperature sensor thermocouples measure the changing water temperature at inlet and outlet of the central receiver. Daily data were collected from each material used as the absorber. Water temperature does increase in the absorber.
- On a clear sky day, a maximum of 73 OC and an average of 70OC of water temperature were recorded using aluminum pipe absorber tube.
- From the result, it can be observed that the parabolic solar trough is a very efficient high temperature water generating system for about five and a half working hours, from 10:00 to 15:30.
- The experimental and the analytical results are very comparable with some acceptable differences.
- The environmental factor plays a major role in the performance analysis of the solar collector. Environmental or weather conditions such as wind and scattered clouds conditions are factors that bring down the efficiency of the solar collector.
- The results of this study give guidance for the possible application of parabolic trough for energy generation.

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