An Experimental Investigation of Influence of Relative Humidity on Thermal Performances of a Parabolic Trough Solar Concentrator

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ABSTRACT
Solar energy is considered by many as a highly prospective alternative energy source due to its ability to meet a significant portion of the world's energy demand. The effectiveness of a solar concentrator depends on operational and atmospheric conditions. This paper presents an experimental analysis of the influence of humidity coupled with inclination angle and mass flow rate on the performance of a parabolic trough solar concentrator. The parabolic trough solar collector underwent experimental testing at the LAUTECH engineering facility in Ogbomoso. It possesses a collector length of 2.1m, an aperture width of 1.2m, an adjustable rim angle of 75^o, 90^o, and 105^o, a focal length of 30 cm, a 10-liter storage reservoir, and variable flow rates of 0.0004 m^3/s, 0.0008 m^3/s, and 0.0012 m^3/s. Temperatures were measured using a 12-channel temperature recorder (SD data logger), solar radiation was measured using a solar meter, relative humidity was measured using an environment meter, and water was used as the working fluid. Thermal performance analysis was conducted to ascertain the impact of relative humidity coupled with tilt angle, mass flow rate, and weather conditions on the solar concentrator's effectiveness. The findings reveals that at higher mass flow rates and a 90° tilt angle, the system has a greater thermal efficacy with weather elements such as solar intensity and relative humidity. Parabolic trough concentrators' performance is determined by the amount of solar intensity focused onto a receiver tube and high humidity in the air reduces the quantity of direct solar radiation that reaches the concentrator and high relative humidity reduces the thermal effectiveness of the system. While relative humidity may not be the main factor influencing the performance of a parabolic trough concentrator, its effects on thermal efficiency and heat exchange should be taken into account when designing and operating such solar thermal systems, especially in environments with varying humidity levels.
Keywords Parabolic Trough Collector, Heat loss, Thermal efficiency, Humidity.
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1. INTRODUCTION

Parabolic trough collectors first appeared in the late nineteenth and early twentieth century's. The first patent was issued in 1907, and the first well-known plant that employed energy supplied by trough collectors was established in Egypt in 1913 (Edenburn, 1976). However, due to low oil costs, solar energy has not been a huge success. It wasn't until the price of oil skyrocketed that this cleared the path for the invention of trough collectors. Currently, these are the most popular thermal collectors; in fact, PTCs contribute more than half of the capacity of concentrating solar power plant equipment (Gunther et al. 2011). A parabolic trough collector (PTC) is built as a parabolic trough mirror that reflects solar energy onto a heat-collecting element (HCE) located in the parabola's focal line. The entire system is supported by a steel structure outfitted with a sun-following motor mechanism. Several numerical and experimental investigations have been conducted to assess the performance of a parabolic trough collector. Edenburn (1976) used an analytical heat transfer model to investigate the thermal performance of a parabolic trough collector. The results are consistent with experimental data from Sandia laboratories in the United States. Dudley et al. (1994) created a heat transfer model to predict a PTC's thermal efficiency and heat losses and the results are in reasonable accord with Sandia's measured data. Foristall (2003) used two heat transfer models based on one- and two-dimensional energy balances implemented in Engineering Equation Solver to anticipate the efficiency and heat losses of a PTC. It was discovered that two-dimensional energy balances are better suited for long receivers. Garcia-Valladares [5] simulated a single- and double-pass parabolic trough collector numerically.

The single-pass numerical model was validated using Sandia National Laboratories' experimental data. When compared to a single pass, the double-pass structure improves the thermal efficiency of the solar collector. More complex models have been developed in recent years, based on a three-dimensional heat transfer study that took into consideration the non-uniformity of the solar radiations that contact the absorber (He et al. (2011). Giostri et al (2012) compared various solar field technologies in terms of both performance at design conditions and annual energy production by conducting energy balances. The findings revealed that the annual solar-to-electrical conversion efficiency for this configuration was 16% higher than that of the baseline

Itabiyi et al. (2021) investigated the Parabolic Trough Solar Concentrator, (PTSC) Water Heater experimentally. With a thermal efficiency of 8.1%, the maximum water temperature obtained from the PTSC water heater with a black-coated receiver was 70^{o}C. According to the findings, the solar concentrator as a source of heat energy performs best with the black receiver. Sangotayo et al. (2019) investigated the performance of a Parabolic Trough Solar Concentrator (PTSC) made of copper, aluminum, and stainless steel receiver pipes. Copper receiver tubes conduct heat more efficiently to the heat transfer fluid than aluminum and stainless steel receiver tubes. Sangotayo and Peter (2020) investigated the impact of thermo-physical characteristics on the performance of a parabolic trough solar collector. The results showed that water-based nanofluids had a considerable impact on the thermal performance of the PTSC. Heat transfer coefficients increase by 20%, 21%, and 14%, respectively, when TiO_2, CuO, and Al_2O_3 are used, while thermal conductivity increases by 23% and specific heat capacity decreases by 30%.

Previous studies on PTCs have never evaluated the effect of humidity coupled with mass flow rate and tilt angle on the thermal performance of a PTC. this work presents an experimental evaluation of the effect of humidity coupled with mass flow rate and tilt angle on the thermal performance of a PTC. The Experimental Rig was located at the Department of Mechanical Engineering Workshop at the Ladoke Akintola University of Technology Ogbomoso, Oyo State, Lat., Long (8.1335° N, 4.2538° E). A 12-channel temperature recorder was used to monitor the receiver temperature, ambient temperature, inlet and output temperatures, and thermal effectiveness at various parameters were determined

2.0 METHODOLOGY AND MATERIALS

The collector is located in LAUTECH, specifically at the university's Mechanical Engineering Department. Table 1 shows the parameters of the collector, which was developed locally from a segmented mirror. The installed collector is 2.1 meters long and is made up of galvanized steel mounts, lightweight, rigid, and precise segmented mirror material parabolic reflector panels, a structurally efficient galvanized steel torque tube, a tubular receiver, and a manual tracking system. Table 1.0 shows the Parabolic Trough Collector parameters.

2.1 Construction of Parabolic Trough Collector, PTC

The PTC was constructed using a simple process. The receiver and the support structure are the two main components of the parabolic trough system. This section elaborates on the complete explication of each component as presented in Figure 1.0

1. Parabolic Trough: A parabolic shape with dimensions of 202 cm x 135 cm was made using plywood. The plywood was used to give the parabolic trough mechanical stability. A macroscopic creature was glued to the plywood, which was then covered with a sequence of 27 segmented mirrors, each measuring 202 cm x 5 cm. The segmented mirrors were attached in such a way that a parabolic curve was formed. Because of its outstanding reflectivity of 96%, segmented mirrors were used. The reflector is made up of segmented mirrors that are adhered to a plywood substrate.

2. Absorber tube: A Galvanized iron (GI) absorber tube is positioned at the focal point (30 cm) of the parabolic trough. The length of the Galvanized iron is 2.21m, and its internal and external diameters are 0.02905m and 0.03105m, respectively. To improve the effectiveness of solar radiation absorption that is reflected by the reflector, black-coated absorber tubes were used.

3. Support Structure: To improve collector precision and stability, the supporting frame was developed to shift the majority of the weight onto the primary support structure. The construction was built to be easily dismantled and transported. For ease of transportation, the unit was installed on a single frame. The building was designed with wheels to facilitate mobility between the lab and testing areas. A jockey wheel was added to facilitate carrying and positioning the gadget for testing. A threaded strut was made to securely retain the mirror at an angle. Any location must be aligned with the sun. The receiver size was chosen by the availability of local channel sections and the necessary concentration ratio.

Table 1.0 Dimension of the Collector

Descriptions	Black Coated (GI)
Rim Angle(ϕr)	90°
Focal Length(f)	0.30 m
Aperture width (Wa)	1.20 m
The outer diameter of GI (Do)	0.031m
The inner diameter of GI (Di)	0.029m
Length of the cylindrical trough(L)	2.1m
Effective Aperture Area (Aa)	2.42m^2
Concentration Ratio(C)	11.7
Reflectivity of the collector (ρ)	0.9
Absorptivity of the GI ($\propto$)	0.95
Transitivity of the GI (τ)	0.8
Intercept factor (Y)	0.92

2.2 Experimental Set-Up

The experiment utilized steel receivers with a focal point of 30 cm, three different volume flow rates of 0.0004m^3/s, 0.0008m^3/s, and 0.0012m^3/s, and three different collector inclination angles of 75^o, 90^o, and 105^o. The system was implemented in a north-south orientation within the Department of Mechanical Engineering at Ladoke Akintola University of Technology (LAUTECH) in Ogbomoso, Nigeria (LAUTECH). The geographical coordinates of the installation site are 8.1227° North, 4.2436° East, and 347 meters above sea level. A 12-channel temperature recorder outfitted with thermocouples was used to measure the temperatures of several system components, including the ambient temperature, reflector temperature, and exterior and interior temperatures of the receiver. The intensity of solar radiation was measured with a solar radiation meter, while relative humidity was recorded with an environmental meter. The measurements were collected at regular intervals of 2 minutes from 9 a.m. to 4 p.m.,

The data were collected for one representative day to evaluate the efficacy of the PTSC system. Simultaneously, the temperature recorder was used to measure and record the variations in ambient, reflector, outer, and inner temperatures at various locations within the trough. The data were acquired to evaluate the constructed system's effectiveness. Figure 1.0 depicts the experimental arrangement of the system. The researchers conducted a series of experiments using the developed parabolic trough collector system as a heat source for heating receivers, as seen in Figure 1.0.

Figure 1.0 Parabolic Trough Concentrator

2.3 Performance of Parabolic Trough Collector

The purpose of the performance analysis is to establish a thermal characterization of the solar field under various operational situations, such as relative humidity, solar radiation, ambient temperature, mass flow rate, and the single-axis sun tracking mechanism used by the system under consideration. The criteria used to estimate performance included solar field thermal efficiency, usable heat generation from the solar field, fluid mass flow rate, and receiver tracking location.

Thermal Efficiency: The overall efficiency η_c of solar collectors is defined as the ratio of the collector's usable output Q_u to the incident global energy, Q_s, as presented in equation (1)

$$\eta_c = \frac{Q_u}{Q_s} \quad (1)$$

the useful output Q_u for a concentrating collector is expressed as shown in (2)

$$Q_u = \text{m Cp}.(T_O - T_i) = A_a.I_b.\eta_o - A_{abs}.U_i.(T_{abs} - T_a) \quad (2)$$

Where m is the mass flow rate, C_p is the specific heat of water at room temperature is 4.18 kJ/kg°C, $T_O$is the outlet temperature, $T_i$is the inlet temperature, Q_s is the incident global energy, it is the product of incident global irradiance (I) on the collector aperture area (A_a) as written in equation (3)

$$Q_s = A_a.I_b \quad (3)$$

Wher A_a is the effective aperture area, (2.42m^2), and the global irradiance I incident on the collector aperture area was measured using a solar meter, [W/m^2]

The estimation of useful energy, denoted as Qs, is determined through the utilization of equation (4).

$$Q_S = \text{m}C_p(T_2 - T_1) \quad (4)$$

The determination of unused heat, H_L was accomplished by employing equation (5).

$$H_L = Q_{S-}Q_U \quad (5)$$

Where $A_a$is the aperture area, $I_b$is the solar intensity, m is the mass flow rate, Cp is the specific heat capacity, $T_2$is the outlet temperature, $T_1$is the inlet temperature, $T_5$is the ambient temperature.

Mass flow rate formula related to the collector flow rate using equations (6-7)

$$Q_{out} = \dot{m}C_p\,(T_{out} - T_{in}) \quad (6)$$

$$\dot{m} = \rho\dot{V} \quad (7)$$

ρ is the density of water at room temperature, *998.2 kg/m^{3,}* $\dot{V}$ is the volume flow rate, and $\dot{m}$ is the mass flow rate

3.0 Results and Discussions

On the campus of Ladoke Akintola University of Technology, Ogbomoso, numerous observations on the PTSC system were made. Latitude 8.1227° N, Longitude 4.2436° E, and elevation 347 m are coordinates for the setup. The graphs depict data obtained from various experimental runs. The testing started at 9:00 a.m. local time. Five minutes before the actual reading, water was introduced into the receiver tube. Every five minutes, the temperature of the water was tested and recorded to guarantee that the incoming beam radiation was always normal to the reflecting surface. The thermal effectiveness, temperatures, and usable energy of the Parabolic Trough Collector (PTC) were investigated. The effect of solar intensity and humidity on the thermal performance, temperatures, and usable energy of the Parabolic Trough Solar Concentrator system, as well as the effect of tilt angle on the PTC's thermal performance, were investigated as presented in Figures 2-6.

Figure 2.0 depicts the relationship between intensity and relative humidity as a function of local time. Figure 2 depicts the solar intensity profile with relative humidity on a sunny day. The maximum reported solar intensity for the receiving tube was 400 W/m^2 and occurred between 12:56 pm and 1:11 pm. It demonstrates the changing nature of environmental influences. The relative humidity reduces as the local time increases but it is almost constant at 2 pm.

The inlet temperature distribution of the PTC (Parabolic Trough Concentrator) against relative humidity at various mass flow rates is shown in Figure 3.0. It shows that the thermal value at a mass flow rate, m_3, of 0.0012m^3/s has the highest temperature distribution, In contrast to the fluctuating changes shown at mass flow rates of 0.0004 m^3/s and 0.0008 m^3/s for mass flow rates, m_1, and m_2, respectively, it indicates that as relative humidity reduces the inlet temperatures increase.

Figure 4.0 presents the receiver temperature against relative humidity at a varying tilt angle, 75^o, 90^o, and 105^o. It can be inferred that the receiver temperature reached its highest value when the tilt angle was 90 degrees over the whole of the experimental period. It implies that a tilt angle of 90 degrees is the best performance angle of tilt when the collector receives direct sunshine on the reflector with less attenuation in the beam radiation. It indicates that as relative humidity reduces the inlet temperatures increase. The high relative humidity is connected with cloudy or overcast conditions. Cloud cover can considerably reduce the amount of direct sunlight reaching the concentrator, decreasing the system's total energy production. This effect is particularly noticeable in areas where humidity and cloud cover are widespread.

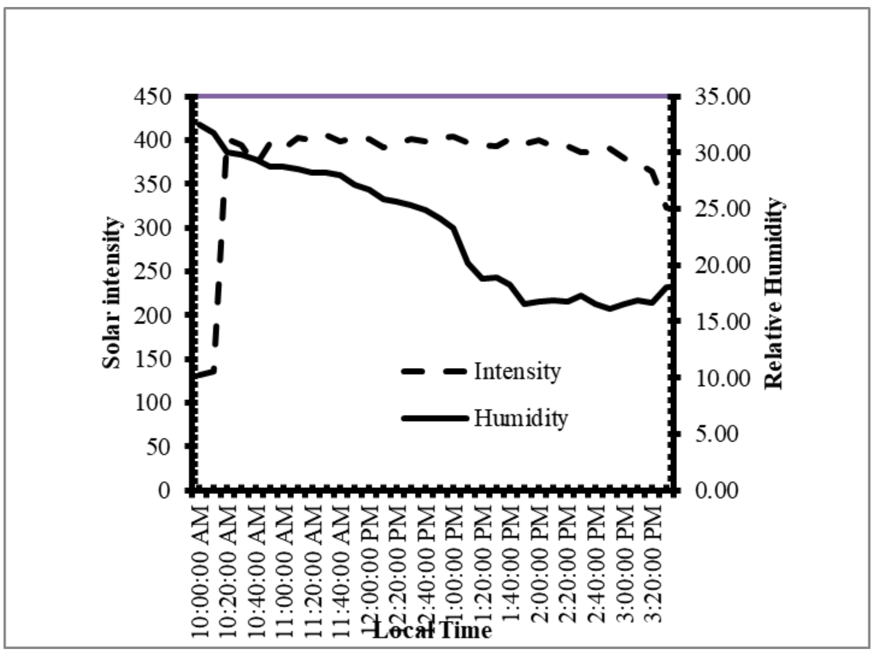

Figure 2.0 Plot of Intensity and Relative Humidity versus Local Time

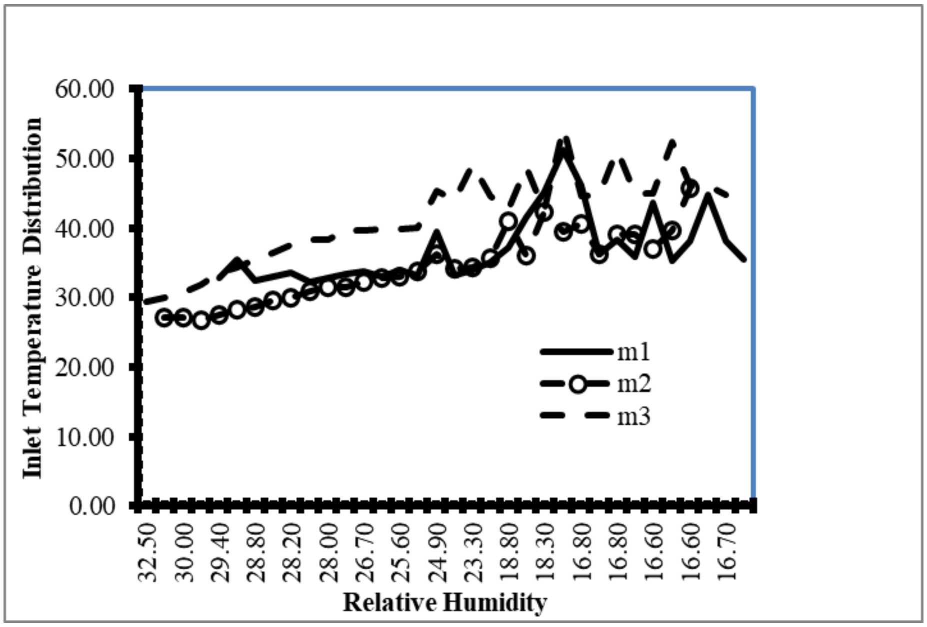

Figure 3.0 Plot of inlet temperature versus Humidity at different mass

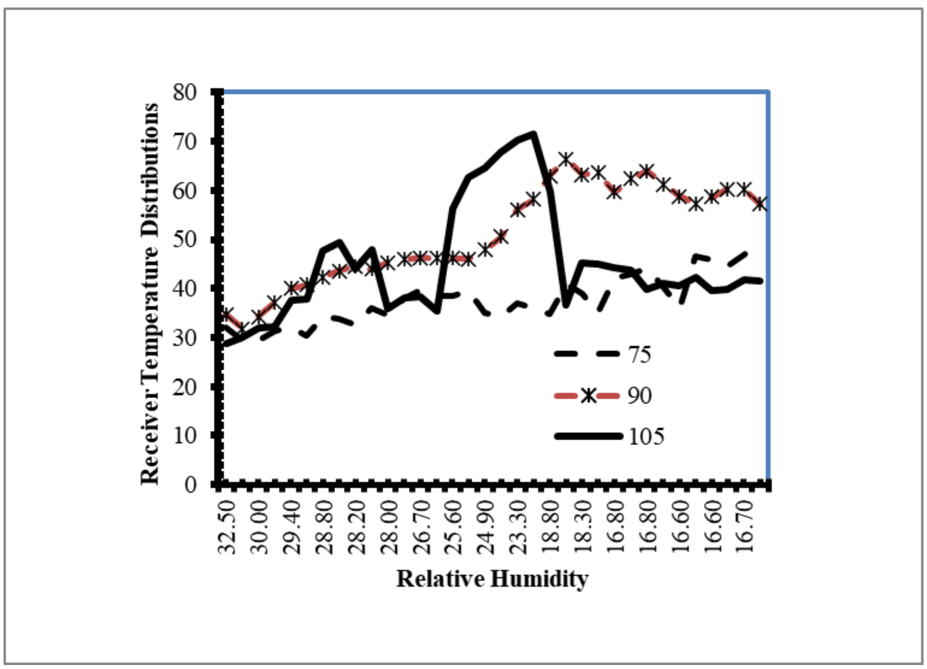

Figure 4.0 Plot of Temperature versus Relative Humidity at different tilt angles

Figure 5 depicts the relationship between usable and unused energy over relative humidity, with average idle energy values of 1000 J and 1500 J, respectively. This indicates that there is a larger quantity of energy available for use. It implies that PTC has good potential to meet the energy shortage of the nation as a result of population explosion and reduce the greenhouse effect.

Figure 6.0 depicts the relationship between the intensity and effectiveness of varying relative humidity levels. Figure 6.0 illustrates the influence of relative humidity on the solar intensity and thermal efficiency of the working fluids in a Parabolic Trough Solar collector. Variations in thermal efficiency as a function of solar intensity and humidity, which influence the efficacy of the PTC system, are primarily the result of daily weather conditions. These diagrams illustrate the influence of cloud cover between the sun and the earth on thermal efficiency, as well as the influence of varying atmospheric conditions on the effectiveness of the PTC system. As shown in Figure 6.0, the calculated average solar intensity and efficiency for the PTC were 400 W/m^2 and 40%, respectively. High relative humidity is associated with cloudy or overcast weather and Cloud cover significantly reduce the quantity of direct sunlight reaching the concentrator, lowering the system's overall energy output. Parabolic trough concentrators' performance is determined by the amount of solar radiation directed to a receiver tube and high relative humidity in the air scatter and absorb sunshine, lowering the quantity of direct solar radiation that reaches the concentrator, hence reducing the thermal efficiency of the system. Parabolic trough concentrators direct solar energy to a receiver tube containing a heat transfer fluid. High humidity impacts the fluid's heat transfer capabilities, potentially increasing heat losses. The amount of water vapour in the air affects convective heat transfer and the overall effectiveness of the process. Also elevated humidity levels, especially in coastal or humid environments, may accelerate corrosion of metallic components, affecting the system's durability and lifespan. Regular cleaning and maintenance are required to ensure optimal performance, especially in humid environments where the deposition of dirt and contaminants can be more pronounced leading to the accumulation of dust, dirt, and other contaminants on the reflective surfaces of the concentrator.

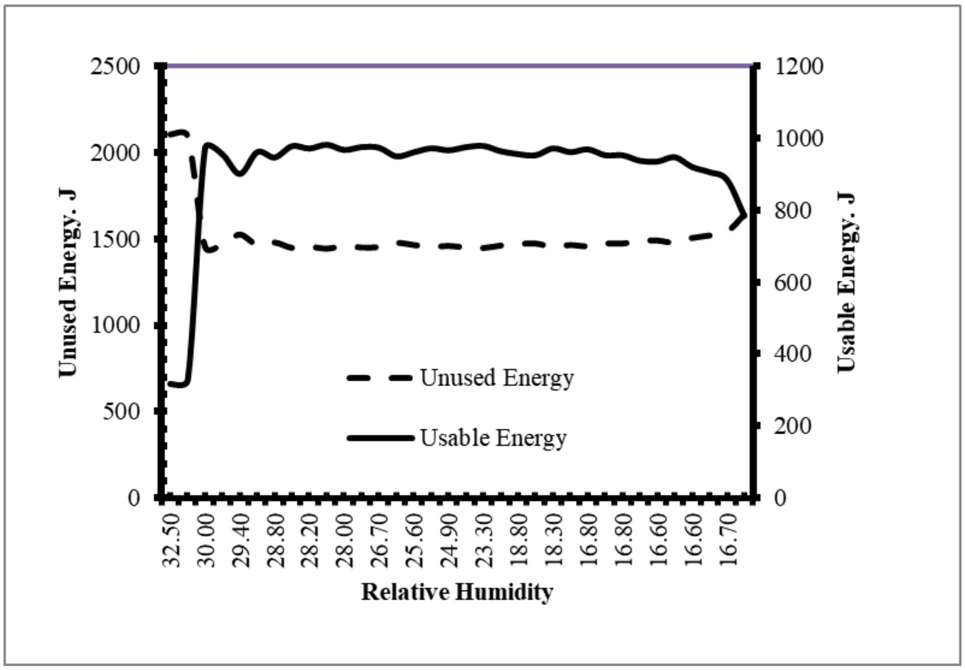

Figure 5.0 Plot of Usable and Unused Energy against Relative Humidity

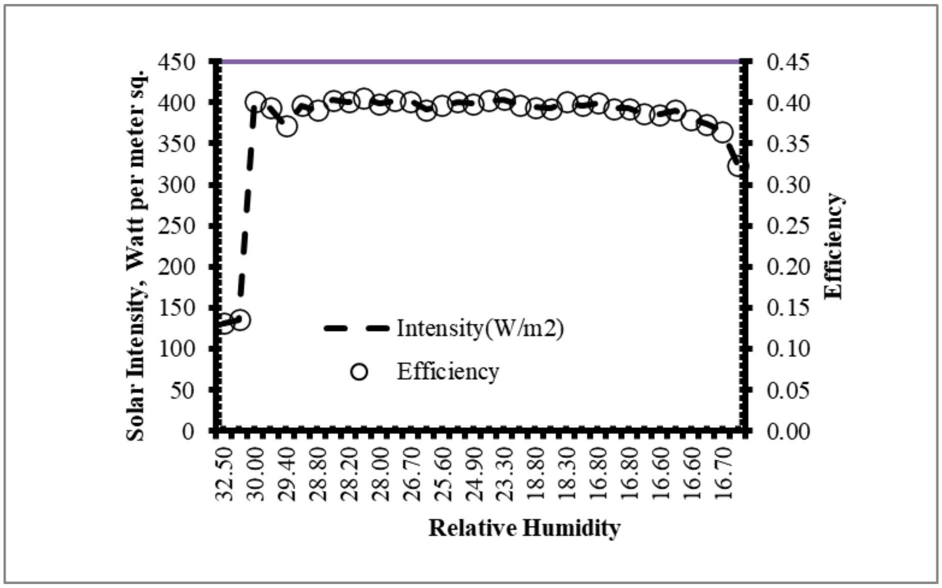

Figure 6.0 Plot Intensity and Efficiency against Relative Humidity

4.0 Conclusions

The majority of human civilization has relied on fossil fuels as its primary source of energy. Utilizing fossil fuels has negative consequences, such as an increase in carbon dioxide (CO_2) emissions. Several operational and meteorological parameters affect the efficiency of parabolic trough solar collectors. This work has examined the influence of humidity coupled with inclination angle and mass flow rate on the operational effectiveness of a parabolic trough solar concentrator. A parabolic trough solar collector was subjected to experimental testing and the setup has a 1.2-meter aperture width, a 2.1-meter collector length, an adjustable rim angle of 75^o, 90^o, and 105^o, a 30-centimeter focal length, a 10-liter storage canister, and a flow meter. A thermal performance analysis was conducted to ascertain the impact of humidity coupled tilt angle, and flow rate on the solar concentrator.

The findings revealed that the system exhibits significant thermal performance with meteorological variables, such as relative humidity and solar intensity at a higher flow rate, and a tilt angle of 90 degrees. Parabolic trough concentrators' performance is determined by the amount of solar radiation focused onto a receiver tube and high relative humidity in the air scatters and absorbs sunshine, lowering the quantity of direct solar radiation that reaches the concentrator. High relative humidity reduces the thermal effectiveness of the system. While relative humidity may not be the primary factor influencing the performance of a parabolic trough concentrator, its effects on thermal efficiency, heat transfer, and maintenance requirements should be taken into account when designing and operating such solar thermal systems, especially in environments with varying humidity levels.

References

Dudley V., G. Kolb, M. Sloan, D. Kearney,(1994) SEGS LS2 solar collector-test results, Report of Sandia National Laboratories, SANDIA94-1884, USA,

Edenburn M.W. (1976) "Performance analysis of a cylindrical parabolic focusing collector and comparison with experimental results", Solar Energy, 18, pp. 437-444

Forristall R.,(2003) Heat transfer analysis and modeling of a parabolic trough solar receiver implemented in engineering equation solver, National Renewable energy Laboratory,

Garcia-Valladares, N. Velázquez,(2009) "Numerical simulation of parabolic trough solar collector: Improvement using counter flow concentric circular heat exchangers", Int. J. Heat Mass Transfer, 52, pp. 597-609,

Giostri A., M. Binotti, M. Astolfi, P. Silva, E. Macchi, G. Manzolini, (2012.)"Comparison of different solar plants based on parabolic trough technology", Solar Energy, 86, pp. 1208-1221,

Gunther M., M. Joemann, S. Csambor, A. Guizani, D. Kruger, T. Hirsch,(2011) Parabolic trough collector, chapter 5 Advanced CSP teaching materials,

He Y., J. Xiao, Z. Cheng, Y. Tao, (2011) "An MCRT and FVM coupled simulation method for energy conversion process in parabolic trough solar collector, Renew. Energy, 36, pp. 976-985, Itabiyi O. E., Sangotayo E. O., Lateef A. K., &Aminu I. F.(2021;) Experimental Analysis of the Parabolic Trough Solar Concentrator Water Heater. *European International Journal of Science and Technology*, 10(7): 1-12.

Sangotayo E. O. and Peter B. A.(2020) Comparative Assessment of the Effect of Thermo-Physical Properties on the Performance of Parabolic Trough Solar Collector, *Journal of Applied Sciences, Information, and Computing,* 1(1): 9–19.

Sangotayo E. O., Waheed M. A., Bolaji B.O. (2019) Thermal Evaluation of a Parabolic Trough Solar Concentrator Using Three Different Receivers, *Journal of Energy Technologies and Policy*, Vol.9, No.5, pp 18-28.