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Experimental Performance Investigation of a Nanofluid Based Parabolic Trough Concentrator in Malaysia

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***Abstract*— Concentrating solar energy system is a potential solar thermal technology and parabolic trough concentrators (PTC) are becoming growingly popular. In this research, both analytical and experimental analyses have been carried out to examine and compare the effect of different operating parameters on PTC performance. Water and water-carbon nanotube (*w*-CNT) are used to explore the performance of PTC system. The optimum receiver diameter is found 51.80 mm for the maximum efficiency of the collector. Performance optimization reveals that mass flow rate and concentration ratio are the inducing parameters on the thermal efficiency and heat removal factor. Investigations show improvement in heat transfer for added nanoparticles. Heat transfer rate is better in laminar flow than in turbulent flow. Experimental results show that with water as heat transfer fluid (HTF), for every 1°C increase in outlet temperature heat gain and thermal efficiency increase at the rate of 0.02 kJ/s and 1.6% respectively. On the other hand, for w-CNT as HTF, for every 100 W/m^2 increase in irradiance, heat gain augments at a rate of 0.23 kJ/s and thermal efficiency upsurges by 7%. Flow rate of working fluids and solar irradiance are found to have respective negative and positive impact on thermal efficiency of the system. Findings of this research work are vital in designing parabolic trough concentrator for supplying industrial process heat (IPH) and running boilers in thermal power plants.**

***Index Terms*— Solar Energy; Thermal collector; Parabolic trough concentrator; Thermal Performance**

I. Introduction

GROWING document energy demand has led researchers and manufacturers to develop and upgrade the renewable energy technologies, of which solar power is considered as the future power [1, 2]. Malaysia has got the best climate settings to go for solar power generation. There is profuse sunlight, low humidity and precipitation throughout the year all over this country. Daylight hours exceed 2500 h/year over most of the terrain, which reaches as high as 3900 h/year in the highlands [3]. Solar electricity has been envisaged to accomplish more than 37% of the nationwide power generation in Malaysia by 2030 [4]. Moreover, vacant flat land close to road networks and transmission grids are also available. So, power generation through concentrated solar energy is seen as the most potential sector to fulfill this target.

Parabolic trough concentrator (PTC) is receiving considerable attention because it can be utilized in many areas, such as cooking, water heating, steam, and power generation [5, 6, 7]. Recently, theoretical, and experimental works have been conducted on PTCs for small to large industrial applications including power generation [8]. PTC is the most mature and organized technology in solar power sector [9] [10, 11]. Moreover, it offers high efficiency with low maintenance and can play a role in mitigating global warming [12, 13, 14]. Application of concentrated solar power (CSP) can curtail 154 million tons of CO_2 emission by 2020 and a 50-MW power plant running on parabolic trough concentrator can help to curb 30 million liters of heavy oil consumption and, thereby eradicate 90,000 tons of carbon dioxide emission [15]. Power generation using PTC-based plants is feasible primarily in the sundrenched countries [16, 17, 18]. PTC is an established technology for solar thermal power generation wherein solar radiation flux can be concentrated up to 80 times that can heat the working fluid up to 400°C [19]. Nevertheless, the performance of such systems depends on the various design and operating parameters [20, 21, 22, 23].

Rehan et al. (2018) conducted an experimental performance analysis of a PTC system having concentration ratio of 11 using Al_2O_3/water and Fe_2O_3/water at concentrations of 0.20%, 0.25% and 0.30% wt [24]. As compared to plain water, authors reported 13% and 11% higher using Al_2O_3 and Fe_2O_3 nanofluids at 2 L/min are under same operating conditions. Kumar and Kumari (2019) experimentally investigated the thermal performance of PTC using multi-walled carbon nanotube (MWCNT) based nanofluid [25]. Thermal efficiency is achieved 3% higher with nanofluid than plain water. Reddy and Ananthsornaraj (2020) designed and developed a PTC prototype of 5.77 m aperture and 80.2° rim angle using evacuated and non-evacuated receiver and assessed its performance in Chennai, India [26]. Authors reported a maximum thermal efficiency of 66% with evacuated receiver and 64% with non-evacuated receiver at 0.12 kg/s.

In the present article, indoor experimental study has been carried out to analyze the thermal performance of water-carbon (*w*-CNT) nanofluid based PTC and compare the performance with conventional water-based PTC system. An analytical thermal performance model of the PTC has been built to predict theoretical performance of the system. It has been observed that nanofluid based PTC delivers superior thermal performance than that with water-based system.

II. Materials and Method

A. Heat transfer fluid (HTF)

A prototype PTC has been designed and fabricated to study its thermal performance using water and water- carbon nanotube (*w*-CNT) nanofluid. Figure1 shows the experimental set up [27]. Thermo-physical properties of water and CNT nanoparticle are shown in Table I.

TABLE I
Properties of heat transfer fluids (HTF) used in the PTC

Material	K (W/m^2.K)	ρ (kg/m^3)	C_p (J/kg.K)	Reference
Water (34°C)	0.652	994	4174	[28]
CNT	3000	1600	796	[29]

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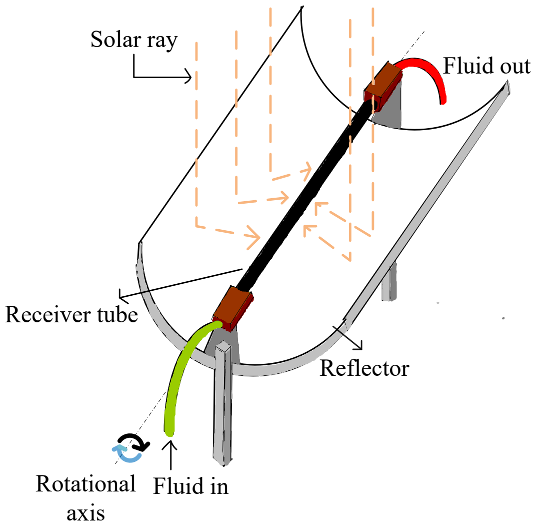

Fig. 1. Schematic of a parabolic trough concentrator

B. *Experimental set-up*

An indoor test setup has been designed to investigate the thermal performance of the parabolic trough concentrator. The experimental setup has been installed in Thermal Laboratory, UM Power Energy Dedicated Advanced Center, University of Malaya, Malaysia. Fig. 2 shows the experimental setup that includes parabolic trough, receiver tube, solar simulator, variacs, data logger, water pump, flow meter, water tanks. Table II presents the specifications of parabolic trough, receiver tube, solar simulator and other auxiliaries.

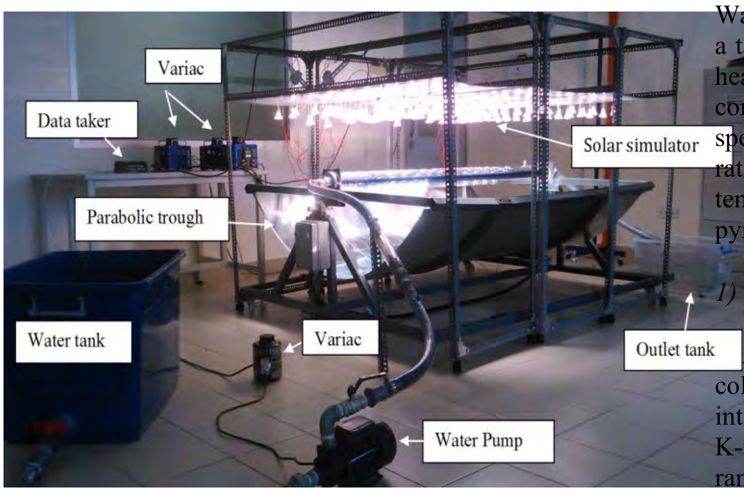

Fig. 2. Experimental setup of the parabolic trough collector (PTC) system

A parabolic mirror, made of aluminum sheet covered with silver electroplating (reflectance 0.90), is supported on a movable iron structure. The receiver tube is aligned laterally of the mirror's focal line and is confined inside an airless glass casing to reduce conduction, convection, and radiation losses. The receiver's exterior is coated by an aluminum–nitrogen/aluminum selective absorbent film to boost heat absorbing capacity. Sunlight rays reflected by the mirrors are engrossed into the absorber tube producing heat that is transported to the heat transfer fluid HTF (water and water-carbon nanotube (*w*-CNT) in present research) flowing through the receiver.

TABLE II
Specifications of parabolic trough, receiver, solar simulator, and auxiliaries

Description	Specifications
Parabolic reflector:	
Material	Aluminum sheet with silver electroplating
Solar reflectivity	0.90
Length	2.0 m
Aperture	1.5 m
Rim angle	85º
Receiver tube:	
Material	Copper tube with selective coating
Solar absorptivity	0.94
Thermal emittance	0.08
Length	2.0 m
Inner diameter	48 mm
Tube thickness	4 mm
Solar simulator:	
Halogen bulb	12 V, 50 W (total 120 bulbs)
Pyranometer	0 to 1280 W/m^2
K-type thermocouple	-75º to 250ºC
Variacs	3 KVA
Heat transfer fluid	Water, water-CNT nanofluid
Pump capacity	Maximum 35 L/min
Mass flow rates (L/min)	0.80, 0.90, 1.10, 1.22 and 1.25

The solar simulator used in this indoor experimental study consists of three halogen light panels, each having 40 bulbs (Brand: OSRAM, 50W, 12V, 7.5A) out of which 20 bulbs are in series and such two series are connected in parallel. Each light panel has a maximum capacity of 2000W, wherein radiation intensity can be varied by variable control AC power supply transformer (variacs). Three variacs each having 3 kVA capacity are used for powering three panels.

Radiation from these halogen light panels is absorbed by the receiver at the focal region after reflecting from mirror. Water or *w*-CNT nanofluid is flown through the receiver from a tank by a centrifugal pump (Model: Pentax CP45), carrying heat from the receiver. The flow rate of the pump is also controlled by a 3 kVA variac. The pump used has the specifications of 5–35 L/min with 9–35 m head and a power rating of 0.5 kW. Two thermocouples are used to record temperature at the inlet and outlet of the receiver tube. Silicon pyranometer is used to measure radiation intensity.

1) *Instrumentation*

A digital data logger (Model: DataTaker DT80) is used to collect data regarding the temperature and irradiation intensity. A variable area meter measures the flow rate. The K-type thermocouples used to measure temperatures have a range between –75º and 250ºC. The silicon pyranometer (Model: LI-COR PY82186) can record irradiance levels from 0 to 1280 W/m^2, within 300 to 1100 nm spectral range and –40º to 75ºC. All the instruments are calibrated following standard operating procedures.

2) *Test condition and data acquisition*

The experiment has been conducted by changing different variables to examine the performance of a PTC at room temperature (ranging 27º to 30ºC). Irradiation intensity has varied between 340–650 W/m^2, while mass flow rate of was regulated between 0.8 – 1.3 L/min. Each parameter is changed autonomously keeping all others constant. Data were collected at one-minute intervals from the inlet and outlet thermocouples of the receiver and from pyranometer. Collected data have been cured and analyzed to explore the impact of temperature, irradiance, and flow rate on PTC performance.

III. MATHMATICAL FORMULATION

Concentration ratio and focus are calculated as follows [30] [31]:

$$CR = \frac{W_t - D_r}{\pi D_r} \quad (1)$$

The useful heat (Q_u) gained can be calculated as [30]:

$$Q_u = F_R\left[SA_a - A_r U_L\left(T_{fi} - T_a\right)\right] \quad (2)$$

$$Q_u = mC_p(T_o - T_i) \quad (3)$$

The collector thermal efficiency is given by [30]:

$$\eta_C = \frac{F_R(SA_a - A_r U_L[T_{fi} - T_a])}{I_b A_a} \quad (4a)$$

$$\eta_C = \frac{Q_u}{I_b A_a} \quad (4b)$$

Solar energy flux engrossed by the receiver is [30]:

$$S = I_b \rho_C \gamma (\tau\alpha)_b K\theta \quad (5)$$

where the incidence angle modifier is given by

$$K\theta = 1 - 6.74 \times 10^{-5}\theta^2 + 1.64 \times 10^{-6}\theta^3 - 2.51 \times 10^{-8}\theta^4 \quad (6)$$

Collector heat removal factor (F_R) has great influence on the performance of PTCSS that can be calculated as [30]:

$$F_R = \frac{m_f C_p}{U_L A_{ro}}\left[1 - e^{\left(\frac{-U_L F' A_R}{m_f C_P}\right)}\right] \quad (7)$$

where F' is the collector efficiency factor which is function of convective heat transfer coefficient h_f and trough's dimensions [30].

$$F' = \frac{1}{U_L\left[\frac{1}{U_L} + \frac{D_{ro}}{D_{ri} h_f} + \left(\frac{D_{ro}}{2K_r} ln \frac{D_{ro}}{D_{ri}}\right)\right]} \quad (8)$$

Convective heat transfer coefficient h_f from the receiver wall to fluid is calculated as [32]:

$$h_f = \frac{Nu_f . K_f}{D_{ri}} \quad (9)$$

For laminar tube flow Nu_f is given as [33]:

$$Nu_f = 4.364 \qquad \text{for } Re_f \leq 2300 \quad (10)$$

For turbulent flow, Nu_f is as follows [32]:

$$Nu_f = 0.023\, Re_f^{0.8}\, Pr_f^{0.4} \quad (11)$$

where $2300 < Re_f < 1.25 \times 10^5$ and $0.6 < Pr_f < 100$.

or

$$Nu_f = 0.0214\left(Re_f^{0.8} - 100\right)Pr_f^{0.4} \quad (12)$$

where $10^4 < Ref < 5 \times 10^6$ and $0.5 < Pr_f < 1.5$.

Free convective heat transfer over the glass is calculated as [34]:

$$Nu_f^{\frac{1}{2}} = 0.60 + 0.387\left\{\frac{Gr\, Pr_f}{\left[1 + \left(0.559/Pr_f\right)^{9/16}\right]^{16/9}}\right\}^{1/6} \quad (13)$$

where 10-5< GrPr < 1012.

Grashof number Gr is given as:

$$Gr = \frac{\beta \Delta T_g D_g^{\,3}}{v^2} \quad (14)$$

Reynolds number and Prandtl number are calculated as follows [30]:

$$Re_f = \frac{4 m_f}{\pi D_i \mu_f} \quad (15)$$

$$Pr_f = \frac{C_P \mu_f}{K_f} \quad (16)$$

The following correlations have been used to determine fluid properties of the water-CNT nanofluid calculated using [35]:

$$\text{Density, } \rho_{nf} = \varphi\rho_p + (1 - \varphi)\rho_{bf} \quad (17)$$

$$\text{Viscosity, } \mu_{nf} = \mu_{bf}(1 - \varphi)^{-2.5} \quad (18)$$

$$\text{Specific heat, } C_{Pnf} = \frac{\varphi\rho_p C_{Pp} + (1-\varphi)\rho_{bf} C_{Pbf}}{\rho_{nf}} \quad (19)$$

Effective thermal conductivity of the nanofluids is calculated by [36]:

$$Keff = \frac{(K_p - K_l)(2{\beta_1}^3 - \beta^3 - 1)\varphi K_l + (K_p + 2K_l)[(K_l - K_f)\varphi\beta^3 + K_f]{\beta_1}^3}{(K_p + 2K_l){\beta_1}^3 - (K_p - K_l)({\beta_1}^3 + \beta^3 - 1)\varphi} \quad (20)$$

where $\beta_1 = 1 + \frac{h}{d}$ and $\beta = 1 + \frac{h}{r}$.

Fluid properties are evaluated at inlet temperature. Heat transfer coefficient is calculated both at volumetric concentrations from 0.025 - 3%.

IV. Results and Discussion

In this section, the outcomes of experimental investigation of a PTC using water and water/carbon nanotube (*w*-CNT) at constant and varying irradiance have been discussed.

A. Thermal performance at constant irradiance

1) HTF: water

The effect of water flow rate on water outlet temperature (as shown in Figure 3) has been examined at 640 W/m2 irradiance and varying the flow rate of water from 0.80 to 1.22 L/min. For every 0.10 L/min increment of water flow rate, outlet water temperature decreases around 2.0^{o}C. That is, for every 1 L/min increase in flow rate water outlet temperature falls by 21^{o}C, which indicates a commendable heat removal capacity of water as an HTF.

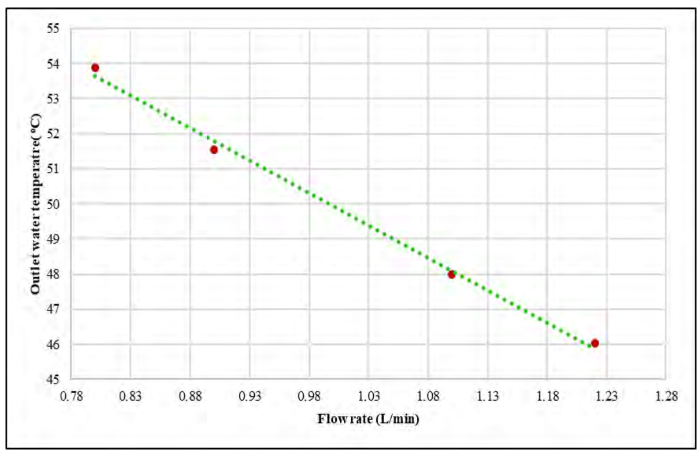

Fig. 3. Outlet fluid temperature as a function of water flow rate

Thermal performance as a function of varying flow rate at a constant irradiance level of 640 W/m2 has been presented in Figures 4 and 5. Heat gain and thermal efficiency increase with increasing flow rate and in both cases experimental results agree well theoretical values. The average discrepancy between theoretical and experimental values is around 4% in case heat gain and 2.5% in case of thermal efficiency. Heat gain increases relatively fast with flow rate and a remarkable 25% upsurge in heat gain is attained when flow rate increases from 0.80 to 1.20 L/min. In contrast, augmentation in thermal efficiency is quite gradual and only a 6% upsurge in efficiency is observed within the same flow range. This is because apart from input energy mode thermal efficiency is controlled by output pattern of the energy, which subsides the efficiency acquisition rate.

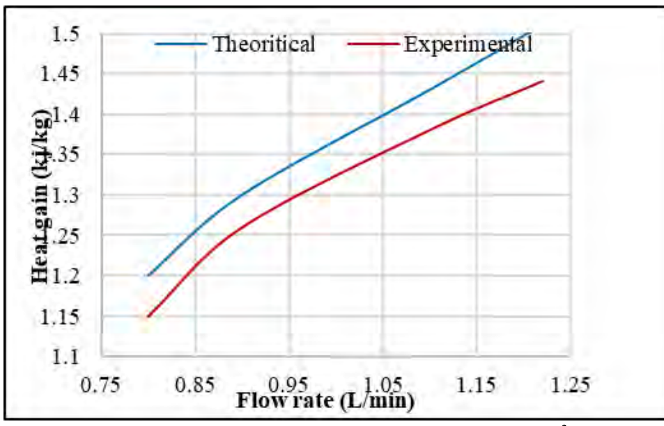

Fig. 4. Heat gain as a function of flow rate (I = 640 W/m^2)

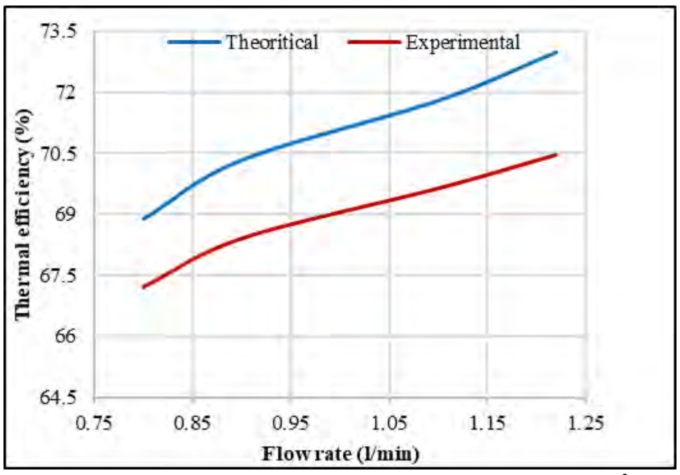

Fig. 5. Thermal efficiency as a function of flow rate (I = 640 W/m^2)

2) HTF: w-CNT nanofluid

Figures 6 and 7 illustrate the consequence of flow rate on heat gain and thermal efficiency, respectively. Water and water-carbon nanotube (*w*-CNT) nanofluid are used for investigation and have been compared with theoretical values. Heat gains and thermal efficiency for *w*-CNT are found higher at 1.15 L/min (1.25 kJ/s and 68.58%) than that (1.24 kJ/s and 67.73%) at 1.25 L/min. As compared to water, w-CNT nanofluid enhances heat gain by 1.23% at 1.15 L/min and 0.98% at 1.25 L/min. Heat gains for water in experiment are 2.60 - 3.49% lower than theoretical values. For w-CNT nanofluid, heat gains are 1.85 - 2.99% lower than theoretical values. Similarly, thermal efficiencies are 4.47 - 5.38% lower for water and 3.63 - 4.74% lower for w-CNT nanofluid than theoretical values.

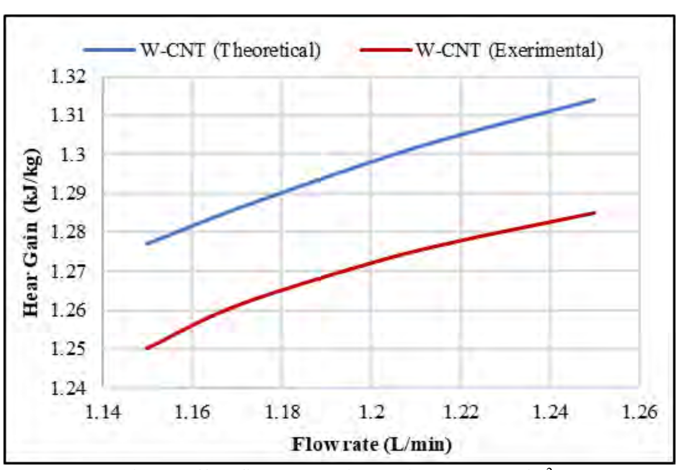

Fig. 6. Effect flow rate on heat gain (I = 640 W/m^2)

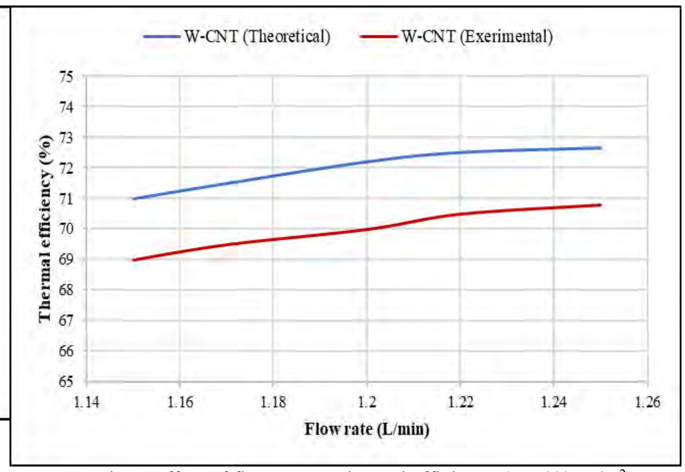

Fig.7. Effect of flow rate on thermal efficiency (I = 640 W/m^2)

B. Thermal performance under varying irradiance

1) HTF: water

Thermal performance is observed under varying irradiance at of 0.90 L/min have been discussed in this section. Water outlet temperature increases linearly with irradiance level. The rise in water outlet temperature reaches its peak of 39.19% at 477.50 W/m^2.

The effect of the outlet water temperatures on heat gain is displayed in Figure 9, where it is manifested that heat gain is linearly proportional to outlet water temperatures. Heat gain increases around 0.02 kJ/s for every 1^{o}C increase in water outlet temperature. Thermal efficiency also increases almost linear with water temperature (Figure 10). For every increment of 1^{o}C water temperature, thermal efficiency increases by around 1.6%

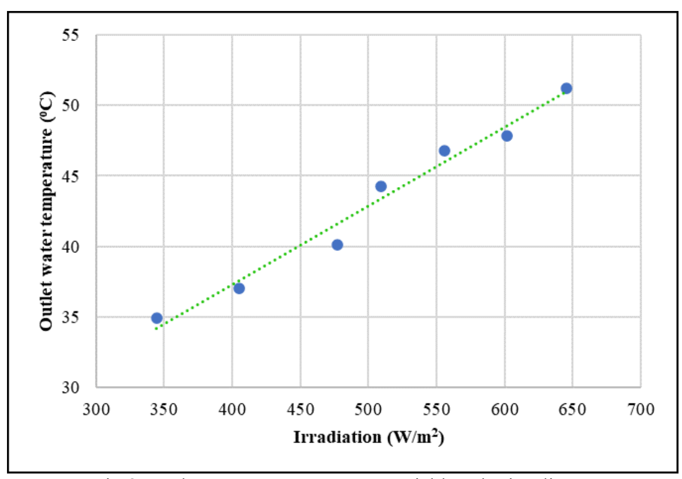

Fig.8. Outlet water temperature at variable solar irradiance

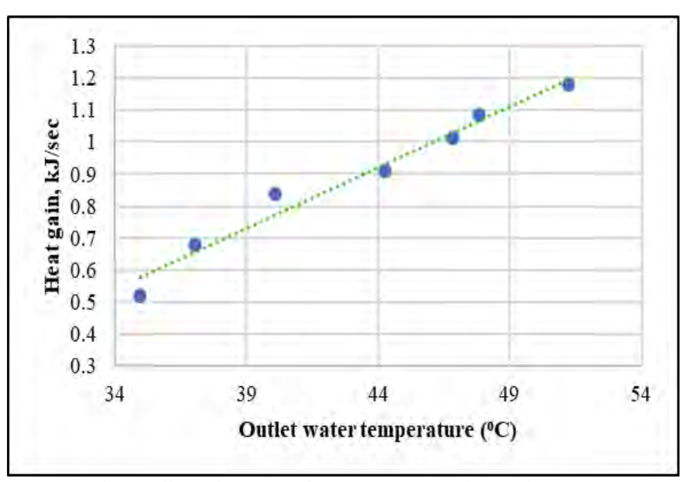

Fig.9. Effect of water outlet temperature on heat gain

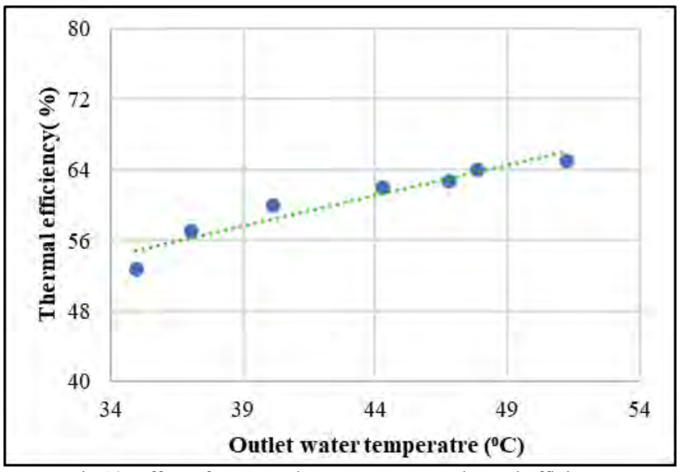

Fig.10. Effect of water outlet temperature on thermal efficiency

The effect of irradiance on heat gain and thermal efficiency (both theoretical and experimental trends) have been demonstrated in Figures 11 and 12. Both heat gain and thermal efficiency upsurge with rising irradiance level though the increment rate is rather bland in case of efficiency. For every 100 W/m^2 increase in irradiance level, heat gain augments approximately at the rate of 0.20 KJ/s, while thermal efficiency upsurges by 4%. These upshots suggest that PTCs can accomplish the best of their performance under high solar irradiance although the enhancement turn out to be sluggish after 650 W/m^2.

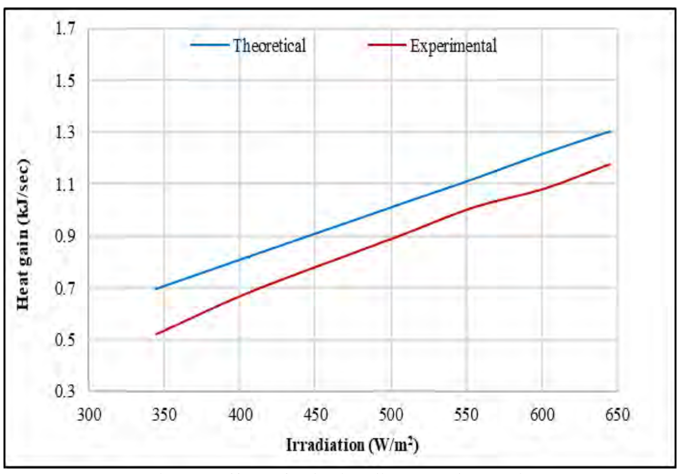

Fig.11. Effect of solar irradiance on heat gain

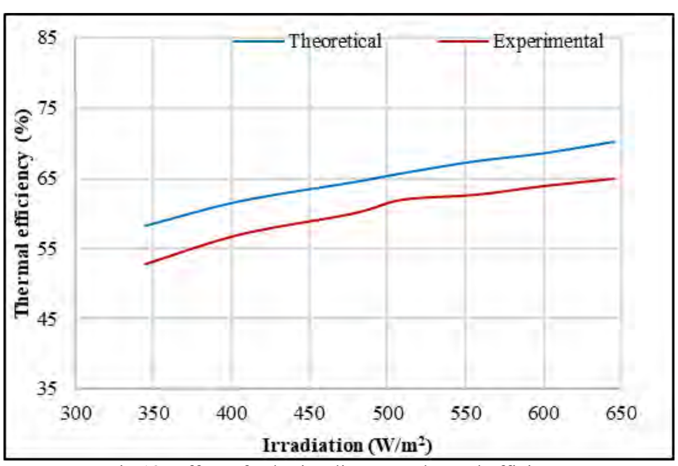

Fig.12. Effect of solar irradiance on thermal efficiency

2) HTF: w-CNT nanofluid

Thermal performance of the PTC has been examined at 1.15 L/min using w-CNT nanofluid as HTF and compared with those obtained using water. Figure 13 illustrates the effect of irradiance on heat gain, while the same upshot for thermal efficiency is presented in Figure 14. Although at low irradiances there is notable discrepancy in heat gain and efficiency values, the experimental outcomes become consistent with the theoretical results at relatively higher irradiance level. Nevertheless, the average rate of increase thermal efficiency becomes dull near 650 W/m^2. For every 100 W/m^2 rise in irradiance level, heat gain augments at a rate of 0.23 kJ/s (Fig. 13) and thermal efficiency upsurges by around 7%.

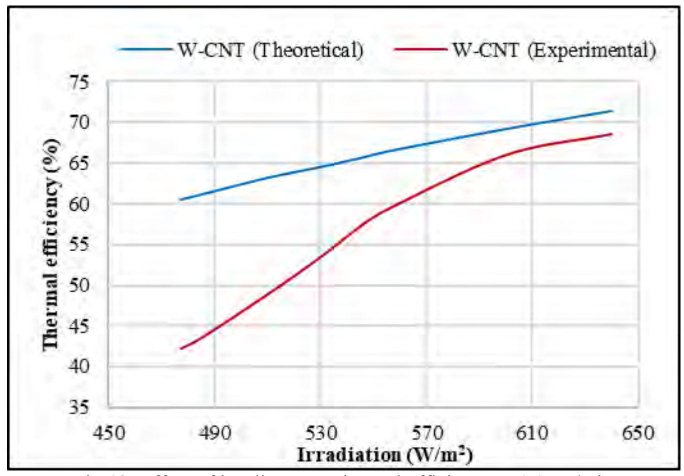

Fig.13. Effect of irradiance on thermal efficiency at 1.15 L/min

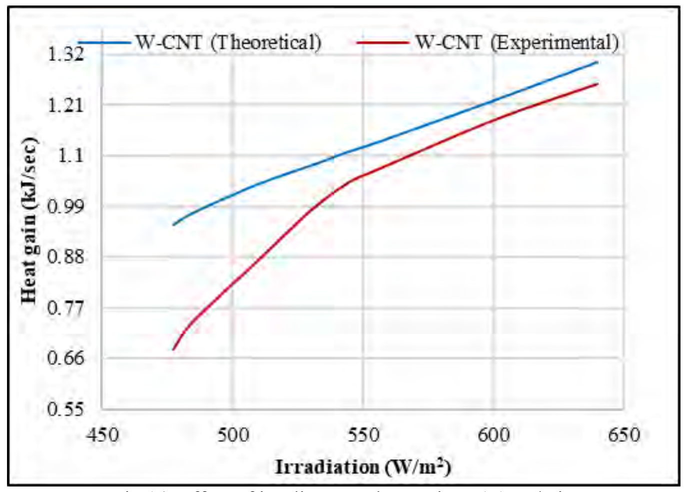

Fig.14. Effect of irradiance on heat gain at 1.15 L/min

V. CONCLUSION

Experimental investigation on the consequence of flow rate, irradiance, etc. on the thermal performance of parabolic trough concentrator using water-CNT nanofluid as HTF have been investigated through indoor experimentation. The ensuing inferences are as below:

- Average discrepancy between theoretical and experimental values are around 4% in case heat gain and 2.5% in case of thermal efficiency.
- Increment of flow rate decreases outlet temperature. For every 1 L/min increase in flow rate water outlet temperature falls by 21°C.
- For water, heat gain and thermal efficiency increase at the rate of 0.02 kJ/s and 1.6% respectively for every 1°C increase in outlet temperature.
- For w-CNT, heat gain and thermal efficiency at 1.15 L/min are 1.25 kJ/s and 68.58% respectively, while those at 1.25 L/min are 1.24 kJ/s and 67.73% respectively.
- For w-CNT, for every 100 W/m2 increase in irradiance level, heat gain augments at a rate of 0.23 kJ/s and thermal efficiency upsurges by around 7%.

The above analytical and experimental study has been carried out with indoor solar simulator for a limited spectral range of solar insolation. Outdoor experimental investigations are highly recommended since indoor facilities cannot simulate the variations of the real-world ambience. Additionally, investigations with other nanofluids should be conducted to ascertain the selection of better HTF.

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NOMENCLATURE

Symbols:

A_a	:	Trough aperture area (m^2)
A_{ro}	:	Receiver outer circumferential area (m^2)
C_p	:	Specific heat capacity of fluid (J/kg.K)
D	:	Diameter (m)
D_{ri}	:	Receiver inner diameter (m)
D_{ro}	:	Receiver outer diameter (m)
F'	:	Collector efficiency factor
f	:	Focus of the trough
F_R	:	Heat removal factor
Gr	:	Grashof number
h	:	Heat transfer coefficient ($W/m^2.K$)
I_b	:	Direct beam irradiation (W/m^2)
K	:	Thermal conductivity (W/m.K)
K_r	:	Receiver thermal conductivity (W/m.K)
K_Θ	:	Incidence angle modifier
L	:	Length of the trough (m)
m	:	Mass flow rate (kg/s)
Nu_f	:	Nusselt number for air
Nu	:	Nusselt number
Pr_f	:	Prandtl number for air
Pr	:	Prandtl number
Q_u	:	Useful heat gain (W)
Re	:	Reynolds number
S	:	Absorbed radiation
T_a	:	Ambient temperature
T_{fi}	:	Inlet fluid temperature
U_L	:	Heat loss coefficient ($W/m^2.K$)
v	:	Fluid velocity (m/s)
w	:	Water
W_t	:	Width of the trough (m)

Abbreviations:

CNT	:	Carbon nanotube
w-CNT	:	Water-CNT nanofluid

Greek symbols:

α	:	Absorptance of the receiver
Θ	:	Incidence angle
β	:	Temperature coefficient of thermal conductivity
μ	:	Viscosity (Pa.s)
ρ	:	Density (kg/m^3)
η_c	:	Collector thermal efficiency
ϑ	:	Kinematic viscosity (m^2/s)
ρ_c	:	Reflectance of the mirror or concentrator
φ_r	:	Rim angle
τ	:	Transmittance of the glass cover
$(\tau\alpha)_b$	:	Transmittance-absorptance product for beam radiation

Subscripts:

f	:	Fluid
nf	:	Nanofluid

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