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Experimental and Theoretical Performance Investigation of Parabolic Trough Collector for Industrial Sector in the Region of Taxila

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Abstract- Concentrating solar collectors are currently being used for industrial process requiring heat applications. This research aims to investigate the thermal performance of parabolic trough collector (PTC) in Taxila for industrial applications. For this purpose, PTC was designed and developed. Thermal performance parameters including exit temperature of heat transfer fluid (HTF), useful heat gain and thermal efficiency of developed system have been evaluated at different mass flow rates of HTF, optical efficiencies and concentration ratio using ethylene glycol as HTF. Investigations of performance measures were carried out theoretically as well as experimentally. Experimental results showed that the obtained exit temperatures, useful heat gain and thermal efficiencies were in ranges of 357.0-374.9K, 2.02-2.71kW and 21.2-22.7% respectively. The deviation between experimental and theoretical results was found to be less than 8.3 %. Theoretical investigation also showed that thermal performance changes insignificantly when mass flow rate exceeds 0.092kg/s. The PTC achieved higher values of exit temperature of 413.6K, useful heat gain of 4.46kW and thermal efficiency of 37.5%during summer solstice as compared to exit temperature of 338.1K, useful heat gain of 1.15kW and thermal efficiency of 9.6% during winter solstice. Higher values of performances measures were obtained at higher concentration ratio of 33.8as compared to lower concentration ratios of 24.1. The findings of this research are useful for industries requiring process heating during food processing, dairy, beverage and paper manufacturing.

Keywords- Parabolic trough collector; Exit temperature; Useful heat gain; Thermal efficiency; Optical efficiency.

I. Introduction

. In this modern era of technological advancement, dependence on depletable energy resources for fulfilling the energy requirements is not considered as a wise decision. This has resulted in threatening situation especially for developing countries. Pakistan is a developing country which is located in South Asia with the population of more than 210 million. Currently, the country is facing worst energy crisis due to wrong decisions at policy levels during the last two decades. In early 1980s, the country's economic growth rate increased due to political and economic changes around the globe which resulted in increased per capita income. The exports also elevated with the improvement in stability and development of new economic zones. This resulted in population growth and improved living standard which led to increase energy requirements manifolds till 1990s.However, the available infrastructure was not able to fulfil the soaring energy demands. To overcome these problems, the government took firefighting decisions and focused on meeting energy demands by utilizing commercial fuels such as coal and fuel oil. Since these commercial fuels were not available locally, therefore the government was unable to extend the generation capacity as per market demand. This resulted in worst energy crisis in 2007-08[1].The situation got aggravated with urbanization and has hampered the development of industrial sector. The conventional fuels such as coal, fuel oil, gas, liquified petroleum gas (LPG) and electricity are used for primary energy requirements with major share of gas (47%) and oil (31%) [1]. The significance of energy in industrial sector cannot be denied as most of the processes rely on the energy usage. However, the use of conventional fuels in this sector is not encouraged due to health and environmental concerns and rise in fuel prices [2, 3]. Therefore, the developed nations are focused on solar thermal energy for industrial applications due to its advantages including cleanliness, inexhaustibility and sustainability [4].The parabolic trough collector (PTC) is one of the most matured technology which can be used for employing solar thermal energy for industrial heat applications[5]. A number of studies have been performed to evaluate the performance of PTC for different domestic and commercial applications. Akbarzadeh and Valipour[6] investigated the impact of corrugated tube on thermal performance of PTC by varying rib height to diameter ratio and pitch to diameter ratio. The study revealed that thermal performance of PTC enhanced by increasing rib height ratio and reducing the pitch ratio. Donga and Kumar[7]evaluated the thermal performance of PTC by identifying the effects of receiver tube misalignment, receiver tube diameter and reflector slope error on PTC performance. The results of study showed that receiver tube misalignment, receive tube diameter and reflector slope error affected the performance of collector. It was also found that intercept factor and overall collector efficiency decreased by up to 11% under the influence of receiver tube misalignment and reflector slope error. Ehyaei et al. [8]performed energy, exergy and economic analysis of PTC and compared the performance of PTC using water based and thermal oil VP-1 based nanofluids. The authors found that the addition of nanoparticles in both base fluids did not enhance the performance of system considerably. Noman et al. [9] employed PTC for a solar cooking system and found favourable results with improved efficiency. The performance of circular and elliptical receiver tubes in PTC was compared by Jebasingh et al. [10] using water as working fluid. It was found that useful rate of heat transfer increased due to increased heat absorption surface and reduced thermal losses in elliptical receiver tube. The effects of various parameters on the performance of PTC were investigated by Norouzi et al.[11].These effects include rotational speed, receiver tube material, mass flow rate of working fluid and nanoparticles concentration. The results indicated that upto15% increase in thermal efficiency can be achieved with proper selection of rotational speed of receiver tube. Valizade et al. [12] studied the thermal behaviour of direct absorption solar PTC using copper metal foam in receiver tube. Three receiver tube configurations namely fully porous, semi porous and porous-free copper foam were investigated and the results were compared with each other. The experiments were conducted with different flow rates and inlet temperatures. Increase in flow rate and decrease in inlet temperature resulted in improved efficiency. The performance of receiver tube with fully porous and semi porous metal foam configurations was found comparatively higher than porous free configuration. Rehan et al. [13]evaluated the experimental performance of PTC using metal oxide based nanofluids and found favourable enhancement in the efficiency of PTC system.

Pakistan is located in one of the sun-drenched clearings of the world where the sun shines for 7-8 hours daily and approximately more than 2300-2700 hours annually[1]. The daily and yearly average global solar irradiation are 5.5-6.0kWh/m^2 and 1800-2200kWh/m^2 respectively. Taxila is a city located in Pothohar Plateau which has large potential for solar energy applications like many other solar rich areas of Pakistan[14].Recognizing the considerable potential of solar energy application, PTC systems can be employed for industrial applications.

The purpose of this research work is to investigate the performance of parabolic trough collector in the region of Taxila. The performance of PTC is evaluated through exit temperature of heat transfer fluid (HTF), useful heat gain and thermal efficiency which are influenced by key parameters of solar mass flow rate of HTF, optical efficiency and concentration ratio of PTC. Hence the effect of these key parameters on the performance of PTC is investigated in this research work. The results of this research will provide foundations for PTC systems application in industrial sector of Pakistan.

The present work is organized as follows. Section II describes the methodology and governing equations used for the performance investigation of parabolic trough collector. The section also describes the assumptions considered during the study. Section III presents the experimental setup and specifications of the PTC system and describes the instruments used for measurements. The working mechanism of PTC system has also been provided in this section. Section IV provides the theoretical and experimental results, discussion and comparisons. Finally, the results of study have been concluded in section V.

II. METHODOLOGY/GOVERNING EQUATIONS

The amount of solar radiations absorbed by the receiver tube is influenced by the optical efficiency of parabolic trough collector. Optical efficiency is defined as the ratio of energy falling on reflector of PTC and energy absorbed by the receiver tube. It is calculated through the expression given in equation 1.

$$\eta_o = \rho_c \tau_v \alpha_r \gamma \left[\left(1 - A_f \tan\theta \right) \cos\theta \right] \quad (1)$$

The solar radiations falling on the surface of parabolic trough collector are reflected by the reflective geometry of the parabolic trough. These reflected radiations fall on the receiver tubes of PTC where

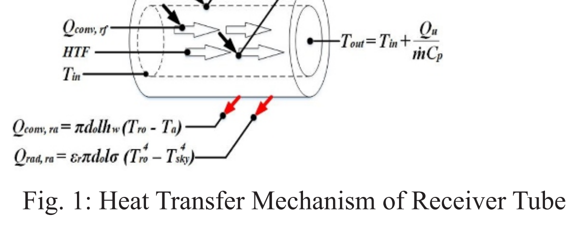

Fig. 1: Heat Transfer Mechanism of Receiver Tube

they are absorbed by the receiver tube material. The heat transfer fluid passing through the receiver tube absorbs the heat energy of receiver tube through convection which is called useful heat gain (Q_u). The heat transfer mechanism of receiver tube is shown in Fig. 1.

The mathematical modelling approach of parabolic trough collector involves the energy balance between the energy absorbed by the receiver and energy delivered by the heat transfer fluid. The energy balance states that energy of solar insolation falling on the aperture is balanced by the optical losses from the reflector and receiver tube, energy losses from receiver tube and energy delivered by the HTF. Mathematically, the energy balance can be explained as by the equations 2, 3 and 4 respectively.

$$Q_{rad,ar} = Q_{cond,r} + Q_{loss} \quad (2)$$

$$Q_{loss} = Q_{conv,ra} + Q_{rad,ra} \quad (3)$$

$$Q_{cond,r} = Q_{conv,rf} = Q_u \quad (4)$$

The ratio of useful heat gain and solar energy captured by the aperture area of PTC is known as thermal efficiency. It is expressed by equation 5:

$$\eta_{exp} = \frac{\dot{m}C_p(T_{out} - T_{in})}{DNI.A_{ap}} \quad (5)$$

Theoretically, thermal efficiency is calculated by equation 6.

$$\eta_{th} = F_R\left[\eta_o - \frac{U_L(T_{in} - T_a)}{CR_g.DNI}\right] \quad (6)$$

The mathematical model has been simplified considering the following assumptions.

a) The parabolic trough collector system is in equilibrium.
b) There is one dimensional flow of heat transfer fluid.
c) The optical properties of the employed materials are constant.
d) The sun tracking errors are negligible.
e) The temperature gradient throughout the thickness of receiver tube walls is uniform.

Using the energy balance equations, the performance of parabolic trough collector has been investigated with different flow rates, concentration ratios along with winter and summer solstice.

III. EXPERIMENTAL INVESTIGATION

The experimental setup was developed to investigate the performance of parabolic trough collector system for industrial applications. The experimental setup consists of a supply tank, two PTCs, a storage tank and positive displacement pump. Polished stainless-steel mirror with 0.8mm thickness was used as reflector material for PTC. The receiver tube made of copper material was used. It was coated with black chrome to increase the absorptivity of solar radiations. The field pipeline was insulated with aluminium cladded 0.05m thick glass wool to reduce the conduction losses. The geometrical and optical properties of the developed PTC have been provided in Table I.

TABLE I: GEOMETRICAL AND OPTICAL PROPERTIES OF PTC [15-18]

Geometrical Parameters	
Specification	**Value**
Aperture area of collector (A_{ap})	2 x 8.08m^2 = 16.16m^2
Length of collector (L_c)	2 x 3.048m = 6.096m
Aperture width (W_{ap})	2.652m
Receiver tube outer diameter (d_o)	0.025m
Receiver tube inner diameter (d_i)	0.022m
Focal length (f)	0.663m
Depth of parabola (h_p)	0.663m
Concentration ratio (CR_g)	33.2
Rim angle (φ_r)	90°
Optical Parameters	
Collector reflectance (ρ_c)	0.92
Receiver absorptivity (α_r)	0.95
Receiver emissivity (ε_r)	0.21
Incidence Angle (θ)	20.13°-41.9°
Optical Efficiency (η_o)	0.34-0.46

The parabolic trough collector system was installed at University of Engineering and Technology Taxila, Pakistan (longitude 72.8º N, latitude 33.7º E). The axis of PTC was positioned in north-south direction so that it could track the sun in east-west direction. The ethylene glycol was used as heat transfer fluid due to its higher thermal conductivity, lower dynamic viscosity, specific heat, working pressures and high working temperature ranges[19-21].It is also anti-freezing agents which can withstand greater temperature ranges having low specific heat[22].

The heat transfer fluid was made to flow from supply tank to PTCs to absorb heat energy from the receiver tube which resulted in increased temperature of HTF. After leaving PTCs, the HTF was made to enter in the storage tank where it was again pumped to the supply tank by a positive displacement pump and thereby formed a complete loop. The flow diagram of developed parabolic trough collector system has been provided inFig. 2.

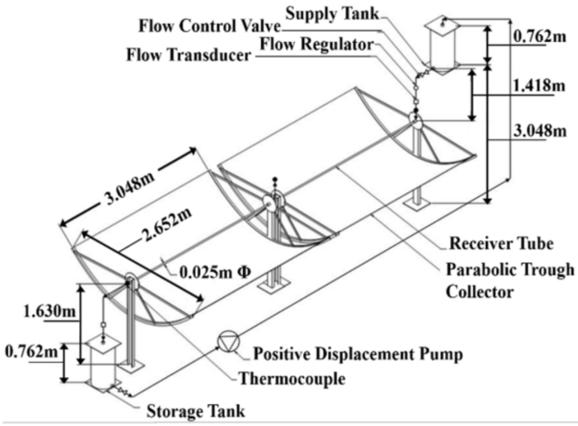

Fig. 2: Schematic Diagram of Developed PTC System

The experimentation was performed during the month of March from 9:00 am to 3:00 pm. The temperature of HTF at the inlet of PTCs was measured by digital thermometers (DS18B20) having accuracy and working temperature range of ±0.5°C and -55-125°C respectively. K-type (chromel-alumel) thermocouples (accuracy: ±0.2°C and working temperature range: -200-1250°C) were inserted at the outlet of PTCs to measure the temperature of HTF. The weather station (JinZhou Sunshine make, Model: TRM-ZS1) was used to measure wind speed (accuracy: ±0.3m/s), ambient temperature (accuracy: ±0.1°C), direct normal solar irradiance (DNI) (Resolution: 1 W/m^2), relative humidity (Accuracy: ±2% RH) and dew point temperature (Accuracy: ±0.2°C). The rotameter was used to control the flow rate of HTF, whereas the electronic flow transducer was employed for continuous data monitoring of flow. All the raw data were collected and recorded by data acquisition system during the experimental runs.

IV. Results and Discussion

The operating conditions under which the performance of parabolic trough collector system was investigated has been provided in TABLE II.

TABLE II: OPERATING CONDITIONS OF PTC SYSTEM

Operating Parameter	Value
Direct Normal Irradiance (DNI)	589-740W/m^2
Mass Flow Rate ($\dot{m}$)	0.0184kg/sec
Inlet Temperature (T_{in})	309-315.8K
Dew Point Temperature (T_{dp})	9.7-11.9°C
Wind Speed	0.4-1.7m/s

The theoretical and experimental exit temperature of heat transfer fluid after passing through receiver tube can be seen in Fig. 3a. It can be observed from the figure that theoretical and experimental exit temperatures were in the range of 361.0-377.8Kand 357.0-374.9Krespectively. It can also be seen that the exit temperature increases with increase in DNIs level. The attained temperature ranges accessible through designed PTC were found consistent with temperature ranges achieved by Ozturk [23]. It is pertinent to mention at the experimental exit temperature is higher than the theoretical exit temperature at afternoon around 14:00pm due to energy already stored in receiver tube and consequent response of tube material to weather conditions.

The theoretical and experimental useful heat gain achieved by HTF is shown in Fig 4a. It can be concluded from the figure that theoretical useful heat gain ranged from 2.19kW to 2.90kW, while the experimental useful heat gain ranged from 2.02kW to 2.71kW. The figure also shows that useful heat gain was lower at the start of day because of less amount of direct normal irradiance at morning time. The gradual increase in the amount of DNIs caused an increase in useful heat gain. The obtained theoretical and experimental thermal efficiencies of PTC have been provided in Fig. 5a. The figure shows that theoretical and experimental thermal efficiencies were found to be within range of 23.0-24.2% and 21.2-22.7% respectively. These values are in close consistency with the values achieved by Soberanis[24]. The figure also demonstrates fluctuations in thermal efficiency at different times of the day which reflects strong dependence of thermal efficiency on DNIs. It must be noted that majority of operations involved in food processing, beverage, dairy and paper industry require temperature in the ranges of 333-363K [3]. Thus the attained temperature ranges can be helpful to cut down the burden on the natural reserves of conventional fuels and thereby fulfilling the energy demands of the industrial sector. As mentioned earlier, the experimental and theoretical results show a strong correlation between amount of DNIs and performance of PTC. The summer season is associated with higher amounts of DNIs, hence, higher temperature ranges can be achieved during the said season.

Theoretical model and energy balance equations have also been validated through the comparison of experimental and theoretical results. Experimental results of parabolic trough collector performance exhibited 8.3% deviation from that of theoretical results. The closeness of theoretical and experimental results depicts that theoretical model has the capability to predict the performance of PTC under different operating conditions. Hence, the system can be employed to predict the performance of PTC under varying flow rates at summer and winter solstice and different design parameters of PTC.

The variation in exit temperature of heat transfer fluid against amount of DNI and different mass flow rates of heat transfer fluid has been provided in Fig. 3b.

The figure shows that exit temperature varies from 316.1K to 377.8K when the mass flow rate of heat transfer fluid was changed in the range of 0.018-0.183kg/sec with transient amount of direct normal irradiance. The figure also demonstrates that exit temperature of HTF decreases with the increase as mass flow rate. Hence the mass flow rate of HTF can be varied depending upon the temperature requirements of industrial applications. It is also be seen that the exit temperature of HTF is directly related to the amount of DNIs. The useful heat gain has been plotted against DNIs with different mass flow rates of HTF in Fig. 4b.The figure describes that the variation of 0.018-0.183kg/sec in mass flow rate of heat transfer fluid increases the useful heat gain from 2.19kW to 3.12kW.Thermal efficiency of PTC against different mass flow rates of HTF and DNIs has been presented in Fig. 5b. It is observed from the figure that during the period when direct normal irradiance ranged from 570W/m^2 to 750W/m^2, a minimum thermal efficiency of 23.0% was observed at 0.018kg/sec mass flow rate while maximum thermal efficiency of 26.1% was achieved at 0.183kg/sec mass flow rate. The figure also demonstrates that the thermal efficiency increases with increase in DNIs. Initially, the thermal efficiency changed abruptly because of differential heat storage capacity of HTF. However, minor increase in thermal efficiency was observed after sometime due to rise in temperature and consequent increase in thermal losses. Thermal performance of parabolic trough collector-based systems entirely depends on optical efficiency of PTC. Since the developed system has been designed to track solar radiations from east to west, therefore, optical efficiency of PTC varies throughout the year which results in variation of performance of PTC. The optical efficiency provides maximum value in summer solstice while minimum value in winter solstice, hence, the performance parameters have been investigated for these solstices.

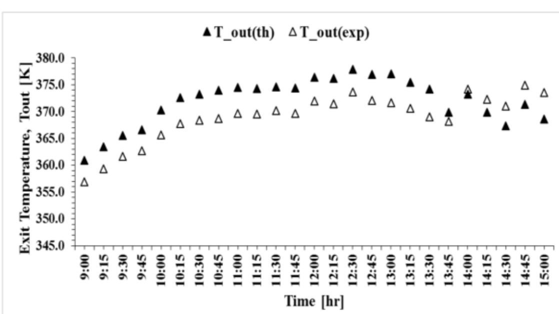

Fig. 3a: Transient Variation of Exit Temperature

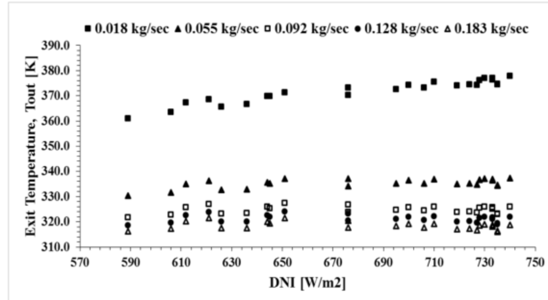

Fig. 3b: Variation of Exit Temperature against various Mass Flow Rates

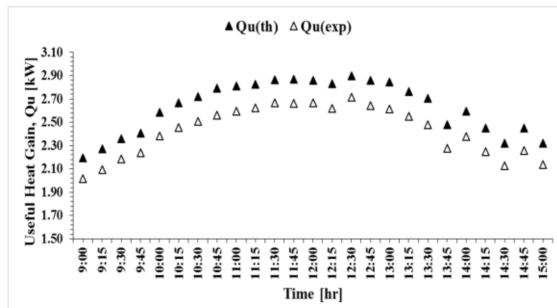

Fig. 4a: Transient Variation of Useful Heat Gain

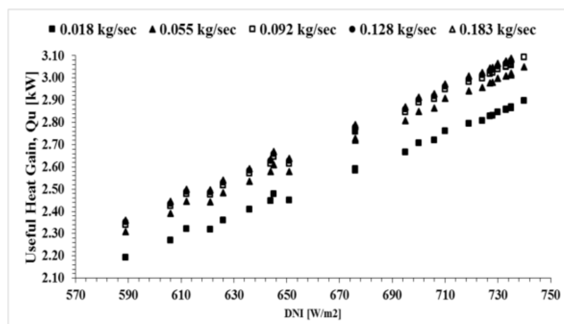

Fig. 4b: Variation of Useful Heat Gain against various Mass Flow Rates

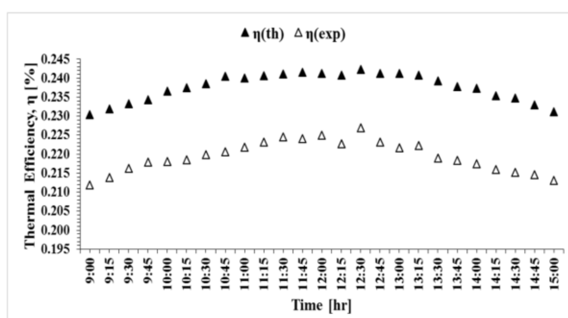

Fig. 5a: Transient Variation of Thermal Efficiency

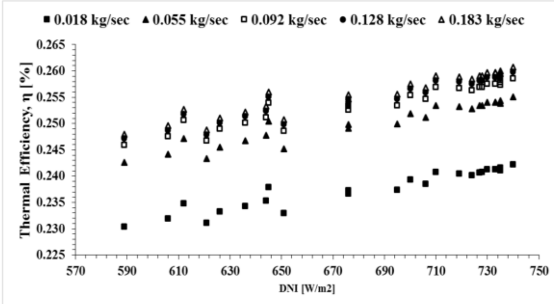

Fig. 5b: Variation of Thermal Efficiency against various Mass Flow Rates

The exit temperatures of HTF in summer and winter solstice have been investigate dat different DNIs and optical efficiencies (Fig. 6a). The figure clearly highlights that during summer solstice, exit temperatures range from 389.8K to 413.6K, while it varies from 329.3K to 338.1K during winter solstice. The minimum optical efficiency of PTC was observed in winter solstice as compared to maximum exit temperature during summer solstice because of differences in optical efficiency. The useful heat gain during summer and winter solstice have been provided in Fig. 7a. Minimum useful heat gain of 0.805kW was observed during winter solstice in comparison to peak useful heat gain of 4.46kW during summer solstice. Fig. 8a highlights the variation in thermal efficiencies of parabolic trough collector against different amount of DNI and summer and winter solstice. It can also be observed from the figure that thermal efficiency ranges from 8.5% to 9.6% during winter solstice, on the other hand, it attained higher values up to 37.5% during summer solstice.

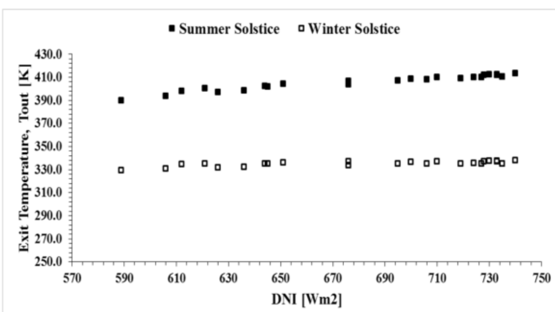

Fig. 6a: Variation of Exit Temperature against Optical Efficiency

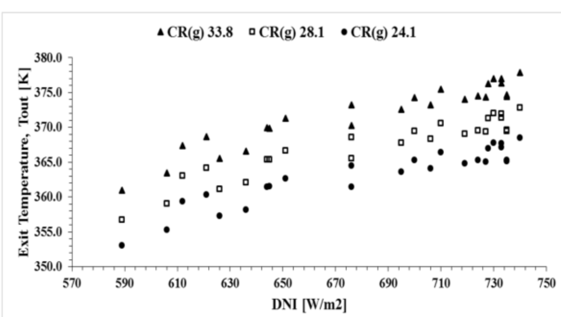

Fig. 6b: Variation of Exit Temperature against Concentration Ratio

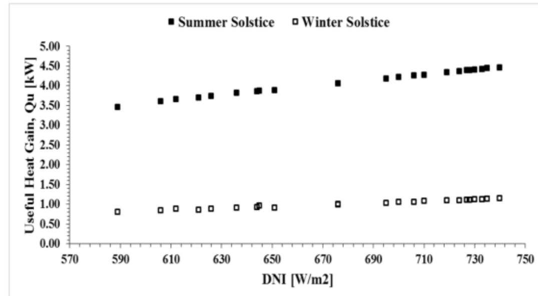

Fig. 7a: Variation of Useful Heat Gain against Optical Efficiency

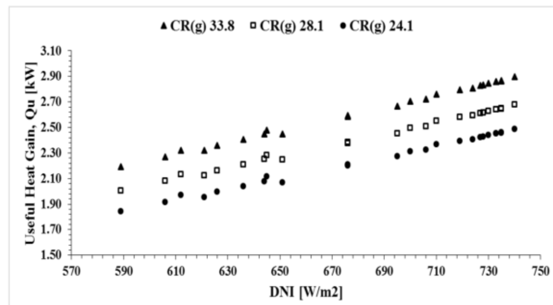

Fig. 7b: Variation of Useful Heat Gain against Concentration Ratio

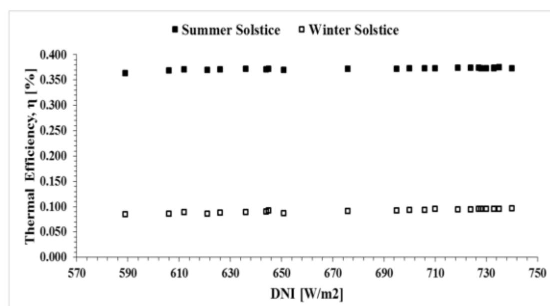

Fig. 8a: Variation of Thermal Efficiency against Optical Efficiency

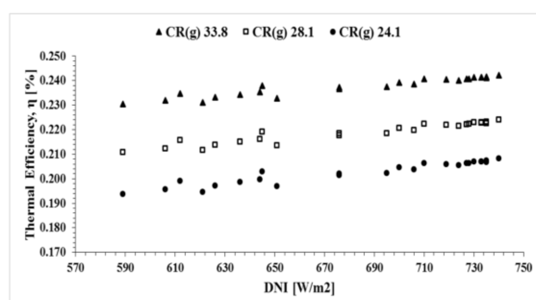

Fig.8b: Variation of Thermal Efficiency against Concentration Ratio

The variation of exit temperatures of HTF against different concentration ratios and DNI have been presented in Fig. 6b. It is evident from the figure that exit temperature of HTF increases with increase in concentration ratio of PTC. For instance, with a concentration ratio of 24.1, exit temperature achieved a maximum value of 368.8K. In comparison, exit temperature raised to 377.8K with concentration ratio 33.8. The variation in useful heat gain at different concentration ratios have been provided in Fig. 7b.The figure clearly depicts that by varying concentration ratio from 24.1 to 33.8, a useful heat gain of 2.49kW to 2.90kW was achieved. This increase of the useful heat gain by increasing the concentration ratio is due to the fact that aperture area of reflector per unit area of receiver tube is enhanced at higher concentration ratio. Fig. 8b represents the change in thermal efficiencies of PTC against variation in concentration ratio. The figure shows that thermal efficiency of PTC increased with increase in concentration ratio. It is evident from the fact that thermal efficiency increased from 19.4% to 24.2% by varying the concentration ratio from 24.1 to 33.8. The main reason behind higher thermal efficiency of PTC with high concentration ratio is the fact that there is small surface area of receiver tube which is coupled with less thermal losses. The same findings have been reported by Manikandan et al. [25].

V. CONCLUSION

In this modern era of development and population growth, sufficient supply of energy is a crucial concern for technological advancement and economic development of the country. Natural reserves of non-renewable energy resources are depleting with the passage of time and are unable to cope up the future energy demands. Furthermore, the use of these energy resources is adversely affecting the environment. In these circumstances, solar energy is a best option in terms of cleanliness, inexhaustibility, and sustainability. Pakistan is rich in solar energy resource. The current study focuses on the potential of solar energy utilization. This has been investigated through experimental and theoretical performance evaluation of solar PTC system. The following conclusions has been drawn from this study.

i. With the developed system, exit temperatures, useful heat gain and thermal efficiencies can be achieved in the range of 357.0-374.9K, 2.02-2.70kW and 21.2-22.7%. This achieved temperature range is in accordance with temperatures required for industrial applications including food processing, dairy, beverage and paper manufacturing.
ii. Maximum difference of 8.3% was observed between theoretical and experimental performance of PTC. Hence, theoretical model can be used for predicting the performance of PTC under different operating conditions.
iii. Thermal efficiency of PTC increases abruptly up to 25.9% with the increase in mass flow rate to0.092kg/s. No significant change in thermal efficiency was observed with further increase in flow rate.
iv. With the developed PTC, higher exit temperature of 413.6K, useful heat gain of 4.46kWand thermal efficiency of 37.5% were achieved during summer solstice. In comparison, lowerexit temperature of 338.1K, useful heat gain of 1.15kW and thermal efficiency of 9.6% were achieved during winter solstice for a given amount of DNIs.
v. The concentration ratio significantly affects the performance of PTC. Higher concentration ratio offers higher values of PTCs performance parameters.

Theoretical study of parabolic trough collector performance provides deep insight of fundamentals for designing the PTC systems for industrial applications. The performance of PTC can be improved with different receiver tube configurations. The receiver tube can be enclosed in a glass tube which will reduce the thermal losses. A secondary reflector on the receiver tube may also provide promising improvement in the performance of PTCs.

NOMENCLATURE

A_{ap}	Aperture area of PTC [m^2]
A_r	Surface area of receiver [m^2]
A_f	Area reduction factor [-]
C_p	Specific heat of HTF [J/kg.K]
Cr_g	Geometrical concentration ratio [-]
DNI	Direct normal irradiance [W/m^2]
d_i	Inner diameter of receiver tube [m]
d_o	Outer diameter of receiver tube [m]
f	Focal length of PTC [m]
F_R	Heat removal factor [-]
h_p	Depth of parabola [m]
h_w	Convective heat loss coefficient [W/m^2.K]
L_c	Length of PTC [m]
$\dot{m}$	HTF mass flow rate [kg/s]
Q	Heat transfer [W]
Q_{loss}	Heat loss [W]
Q_u	Useful heat gain [W]
T_a	Ambient temperature [K]
T_{dp}	Dew point temperature [°C]
T_{in}	Inlet temperature of HTF [K]
T_{out}	Outlet temperature of HTF [K]
T_{sky}	Sky temperature [K]
T_{ro}	Surface temperature of receiver tube [K]
ΔT	HTF temperature rise [K]
U_L	Heat loss coefficient [W/m^2.K]
W_{ap}	Aperture width of PTC [m]

Greek symbols

α_r Absorptance of the receiver [-]
ε_r Emissivity of the receiver [-]
η Experimentally observed thermal efficiency [-]
η_o Optical efficiency of collector [-]
ρ_c Reflectance of the collector [-]
τ_v Transmissivity of the receiver glass [-]
θ Incidence angle [°]
φ_r Rim angle [°]
γ Intercept factor [-]
σ Stefan-Boltzmann constant [5.67 x 10^{-8} $W/m^2.K^4$]

Abbreviations

HTF Heat transfer fluid
LPG Liquified petroleum gas
PTC Parabolic trough collector

Subscripts

exp Experimentally observed value
th Theoretically observed value
cond,r conduction through receiver tube walls
conv,ra convection from receiver tube to ambient
conv,rf convection from receiver tube to HTF
rad,ar radiation from ambient to receiver tube
rad, ra radiation from receiver tube to ambient

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