Design and Simulation of Solar Parabolic Trough with TRNSYS

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Abstract-Pakistan is an energy-starved country and this demand of energy is increasing with every passing day. Fortunately, the country receives ample amount of annual solar radiation which if utilized proficiently and effectively can suffice the domestic as well as the industrial needs. In the present study, a design of 20kW parabolic Trough is proposed. Results of theoretical calculations have been given in detail and the design has been analyzed on TRNSYS software. The resulting graphs well describe the variations of various outputs of the solar field and help to predict the performance of the plant.

Keywords-Parabolic Trough, TRNSYS, Simulation, Rankine Cycle, Solar Irradiance,

I. INTRODUCTION

Parabolic trough collector is the most proven technology to convert solar energy into electricity. It represents the optimal resolution regarding the attainable concentration ratio and the attainable energy production per aperture area in line-focusing solar collectors. The construction of a parabolic trough collector is simple. The solar irradiance incident on the reflective coating of the collector is reflected to a receiver (aligned along its focal length) which carries a heat transfer fluid (HTF). The HTF can then be used in a heat exchanger to give up its energy to water in order to produce superheated steam [i-iii]. These collectors are arranged in various arrays in a solar field and the field can then replace the boiler of a basic steam turbine power plant (Rankine Cycle).

Many researchers have toiled hard in this field to get the maximum output from solar energy. Different design concepts of the steam power plants using synthetic oil as HTF have been discussed [iv]. Lately new approach has been followed of direct steam generation [v-vi]. Herein the feed water enters in the solar field in liquid state while leaves in superheated steam form [vii]. Control systems have been installed to maintain the flow rate of steam [viii]. Thermo-hydraulic behavior of flow has been formulated as well [ix-x]. Further three-dimensional computational fluid dynamic studies were undertaken [xi].

In this research paper a proposed design of Parabolic Trough Power Plant with an average capacity of 20kW is discussed. Lahore has been selected as the location of operation. Theoretical Calculations have been done for the stated power output at reference weather conditions. The results of the calculations are here employed as inputs/parameters in order to model & simulate the performance of the solar field in TRNSYS. During the process a new component (that we shall call PTC) is created in TRNSYS Simulation Studio which is then used in conjunction with a few built-in components of TRNSYS Library.

II. MATHEMATICAL MODEL

Fig. 1 shows the T-s diagram for a basic Rankine cycle. The various reference values and inputs incorporated in the design are shown in Fig 1.

In the first step, the different state points are determined theoretically by analyzing the heat transfer in each component of the cycle. On the basis of these state points, steam flow rate, condenser water flow rate etc. is calculated.

The required size of total aperture area to produce 20kW power output at the reference weather conditions is then found by considering the heat balance between the heat transfer fluid coming from the solar field and steam generated from the Rankine cycle [xii]. Utilizing the Land Usage Factor (Lu), the total solar field area is calculated by:
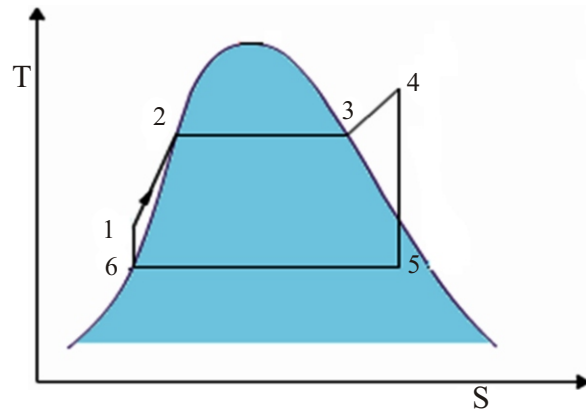
$$A_{field} = A_{aperture} / Lu \qquad (1)$$

Fig. 1. T-s Diagram of Rankine Cycle

TABLE I
DESIGN INPUTS AND REFERENCE VALUES

Power Output	20kW
Turbine Inlet Temperature	300°C
Turbine Inlet Pressure	30bar
Turbine Outlet Pressure	0.1bar
Specific Heat of Water	4.187kJ/kg
Isentropic Efficiency of Turbine	70%
Isentropic Efficiency of Pump	90%
Land Usage Factor	60%
Condenser Water Temperature Difference	10°C
Average Solar Irradiance for Lahore	600 W/m^2
Generator Efficiency	85%

Fixing the area per collector (A_c), the total number of solar collectors required can be calculated by:

$$n = A_{aperture} / A_c \qquad (2)$$

(The complete design of a single unit of Parabolic Trough Collector can be is given in Fig. 2)

G_{actual} represents the actual flux absorbed by the receiver in W/m^2 and can be calculated as follows [xiii]:

$$G_{actual} = G.\alpha.\rho.\tau.\gamma.M \qquad (3)$$

α, ρ and τ denote the optical properties i.e. absorptivity of receiver material, reflectivity of reflective coating & transmissivity of glass envelop respectively. □ is the intercept factor. M is the incidence angle Modifier given by [xiv]:

$$M = \cos\theta_i - 0.0003512\theta_i - 0.00003137\theta_i^2 \qquad (4)$$

(The adopted values of optical properties of the materials are given in Fig. 3)

The useful energy gain of HTF can be calculated by using the relation [xiv][xv]:

Q_u = G.A$_{aperture}$.[LMS (A+B/2(ΔT_i + ΔT_o)] + C (ΔT_i + ΔT_o)/2G + D (ΔT_i + ΔT_o)^3/2G(ΔT_i + ΔT_o)

Q_u = G.A$_{aperture}$[LMS(A+B/2(ΔT_i + ΔT_o)]+C(ΔT_i + ΔT_o)/2G +D(ΔT_i + ΔT_o)^3/2G(ΔT_i + ΔT_o)

$$(5)$$

In (5) A, B, C & D are empirical factors describing the performance of the collector under consideration and their values can be taken from Lippke (1995)[xiv]. M is the incidence angle modifier. L considers end losses. S considers shading of parallel rows. L is given by [xvi]:

$$L = 1 - f.\tan\theta_i / L_{SCA} \qquad (6)$$

Shading of parallel rows is determined by [xvi]:

$$S = L_{spacing} / W.\cos\theta_z / \cos\theta_i \qquad (7)$$

The net Heat Transfer, Q_{net} is given by [xii][xv] :

$$Q_{net} = Q_u - Q_{pipe} \qquad (8)$$

Where, Q_{pipe} accounts for losses in piping.

TABLE II
SPECIFICATIONS OF A SINGLE PARABOLIC TROUGH

Parameters	Value
Collector width	2.4m
Collector Length	2.5m
Aperture Area per Collector	6m^2
Rim Angle	90 degree
Focal Distance	0.6m
Collector Height	2.4m
Receiver Diameter	11.1 mm
Collector Reflective Material	SS 316
Reflective Sheet Thickness	1.5mm
Receiver Material	SS 304L (Black Nickel Coating)
Receiver Thickness	1 .0 mm
Glass Envelop Diameter	20mm
CR	69.13

The mass flow rate m_{HTF} can be found for a constant HTF outlet temperature T_{out} by using [xv][xvi]:

$$m_{HTF} = Q_{net} / C_p.(T_{out} - T_{in}) \qquad (9)$$

Here, C_p is specific heat and T_{in} is the inlet temperature of HTF.

Thermal Efficiency is finally calculated by [xiii]:

$$\eta_{thermal} = Q_u / A_{aperture}.G \qquad (10)$$

The optical Efficiency is determined by using the relation [xiii]:

$$\eta_{optical} = G_{actual} / G \qquad (11)$$

TABLE III
OPTICAL PROPERTIES [2]

Parameter	Value
Absorptivity	0.95
Reflectivity	0.93
Transmissivity	0.94
Incidence Angle Modifier	1
Intercept Factor	0.92

TABLE IV
RESULTS OF THEORETICAL CALCULATIONS
(AVERAGE VALUES)

Parameter	Value
Solar Irradiance	600 W/m^2
Actual Flux absorbed in the Receiver	458.43 W/m^2
Useful Energy Gain	146.3 kW
HTF Inlet Temperature	340 °C
HTF Outlet Temperature	361.2°C
Optical Efficiency	76.4%
Thermal Efficiency	70%
Condenser Water Flow Rate	1.884 kg/sec
Steam Flow Rate	0.0366 kg/sec
Heat Transfer Fluid	Therminol VP-1
HTF Flow Rate	0.003 kg/sec
Total Aperture Area	348 m^2
Total Solar Field Area	580 m^2

III. INTRODUCTION TO TRNSYS

TRNSYS is a transient system simulation program, developed by the Solar Energy Laboratory at the University of Wisconsin - Madison, which has been designed to model the performance of thermal energy systems. Each component in a system is modeled by a separate FORTRAN/C++ Program. The program contains the inputs, parameters, outputs and governing equations of the component. The programs of different components of a thermal system are linked together and controlled by the main TRNSYS program. The outputs of one component become the inputs of the other component and the simulation of the whole system is created by TRNSYS Simulation Studio [xvii].

IV. SIMULATION OF THE SOLAR FIELD

The main purpose of TRNSYS modeling & simulation is to have the weather conditions different from those assumed or considered in design calculations and in this way analyze their effect on the plant performance. In this paper, we create a solar field model rather than the complete power plant model and compare the values of HTF outlet temperature, flow rate, Useful Energy gain etc. with those obtained from the theoretical calculations.

V. TRNSYS PROGRAM

The equations from (1) to (11) are written in C ++ language, coupled to a TRNSYS program and a Parabolic trough Solar field model is created. The process of simulation can be seen in Fig 2, which indicates the various inputs, parameters & outputs of the model. It also indicates the connections between the various components that are linked together to simulate the performance of the solar field. It can be seen that two built in components have been used in TRNSYS Simulation. Type 109-TMY2 is used to provide the weather conditions for Lahore for the specified period of time (one year in our case). Type 65a is the online plotter that is used to create the graphs showing the variations of different quantities over time.

VI. RESULTS OF SIMULATION

Comparing the graphs resulting from simulation with the results of theoretical calculations (see Fig IV), we observe variation. It should be kept in mind that in theoretical calculations we considered a design point. we considered an average value of solar irradiance (600W/m^2).But in actual case the solar irradiance varies between a maximum value of 900W/m^2 in summer and a minimum value of 274 W/m^2 in winter as seen in Fig 3. So the results of simulation also show fluctuations above and below the corresponding values of theoretical calculations. The simulation is done for 8760 hours i.e. one year.
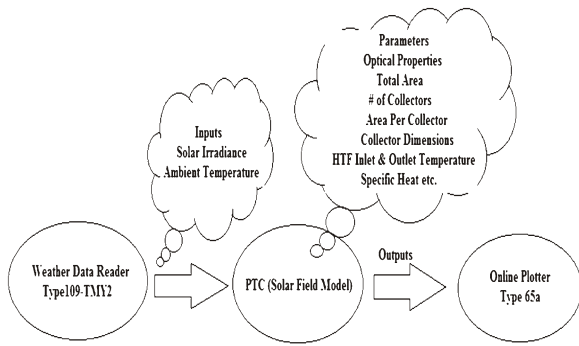
Fig. 2. TRNSYS Simulation Process; the used Components (TYPEs) along with the associated inputs, parameters & outputs

The peak values of the quantities like solar flux absorbed by the Receiver, HTF mass flow rate, Useful Energy Gain are observed at mid summer when the ambient temperature and the solar radiation are maximum. All of these graphs show fluctuations with changing time, days & seasons.
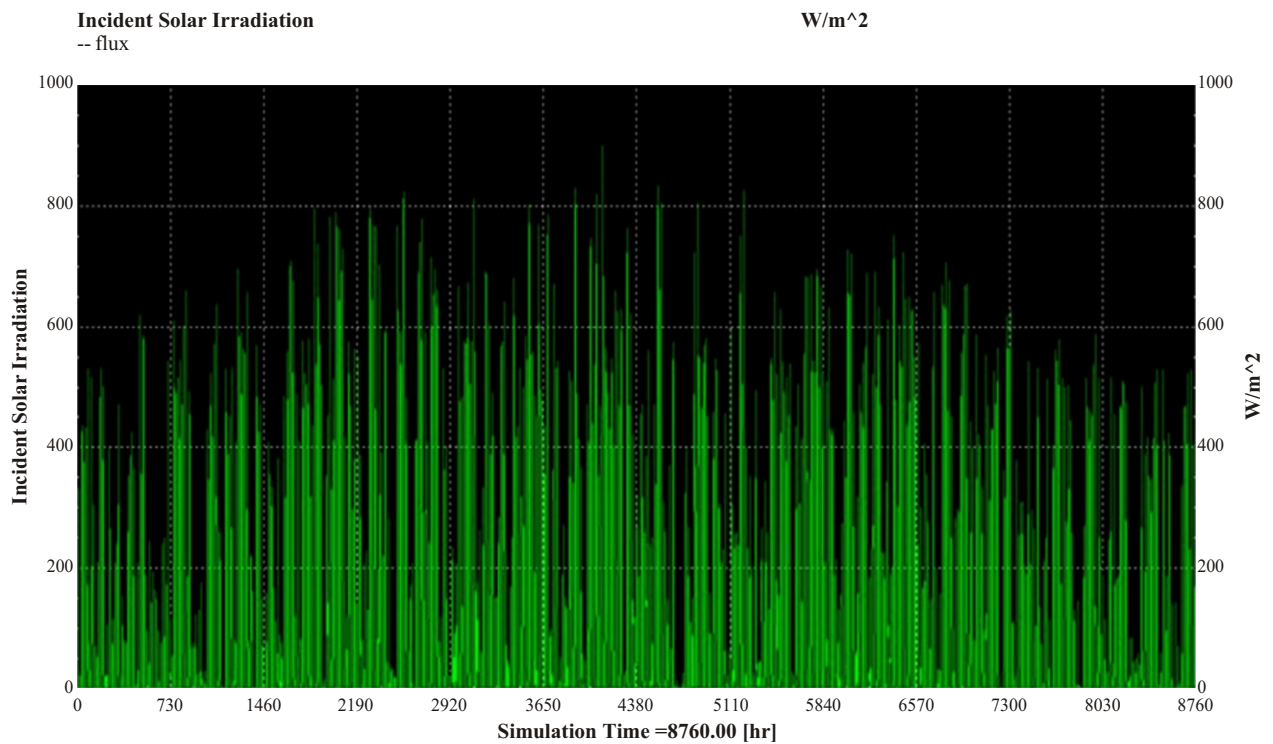

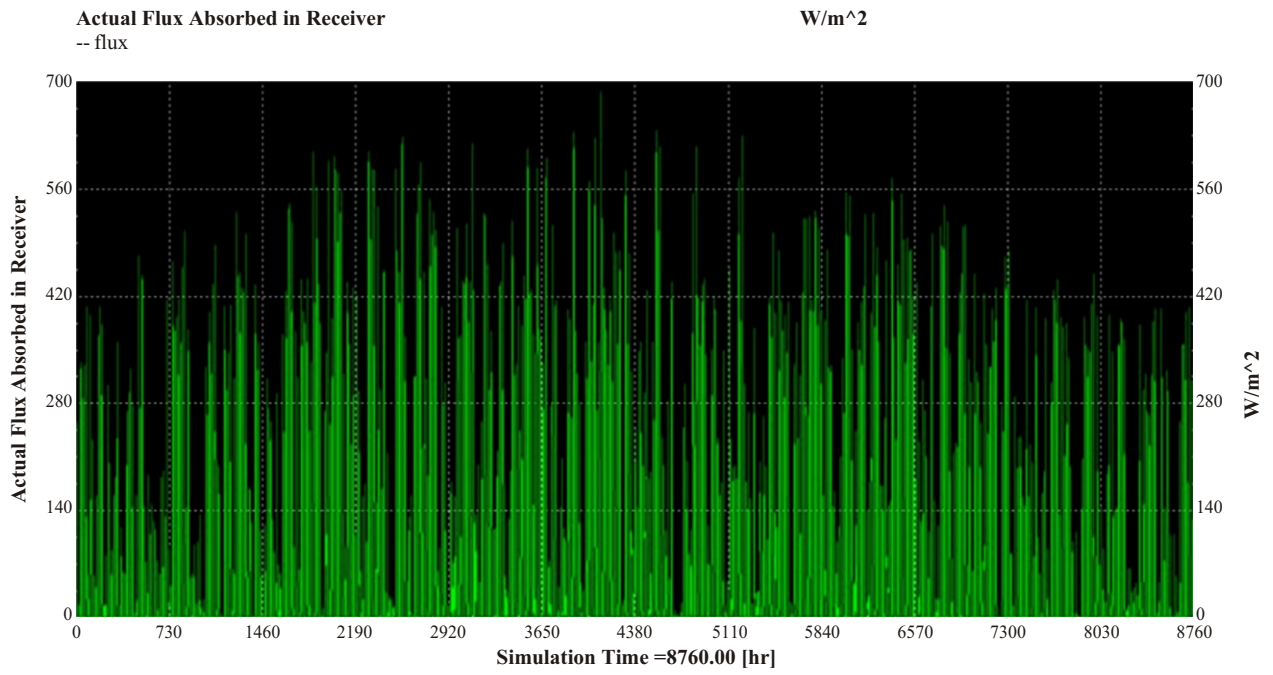Fig. 3. Incident Solar Irradiation for Lahore, Pakistan (TRNSYS Simulation)

Actual Flux Absorbed in Receiver   **W/m^2**
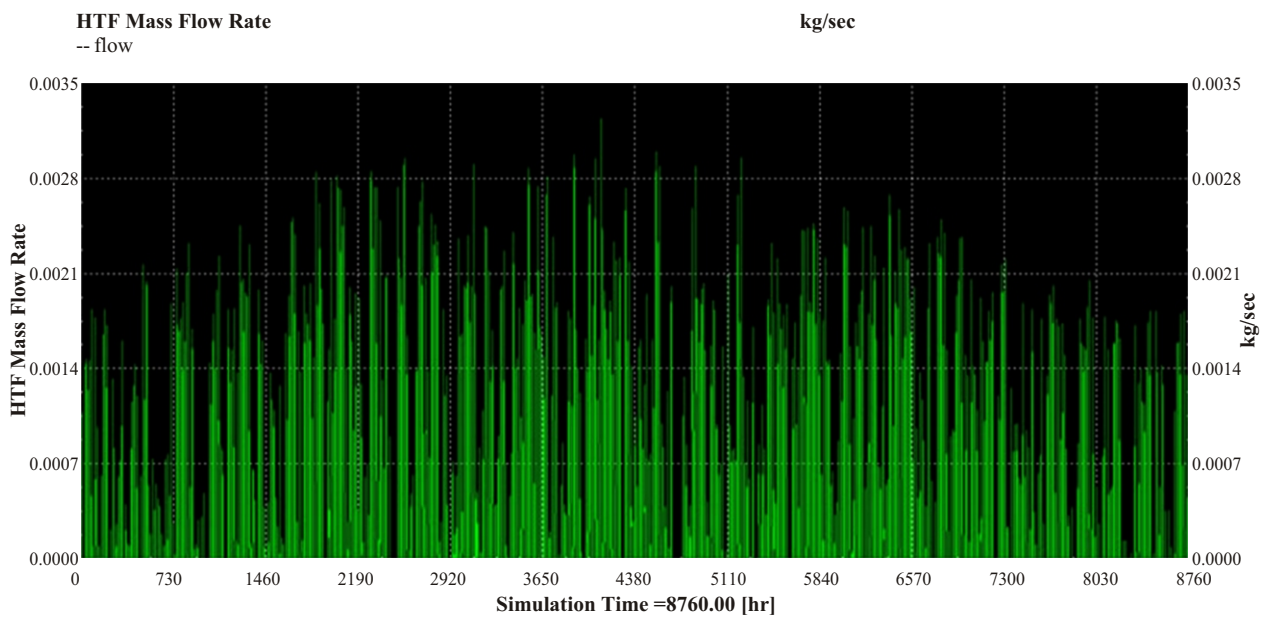-- flux

Fig. 4. Solar Flux actually absorbed by the Receiver

HTF Mass Flow Rate   **kg/sec**
-- flow

Fig. 5. HTF Mass Flow Rate (TRNSYS Simulation)

Useful Energy Gain   **Watt**
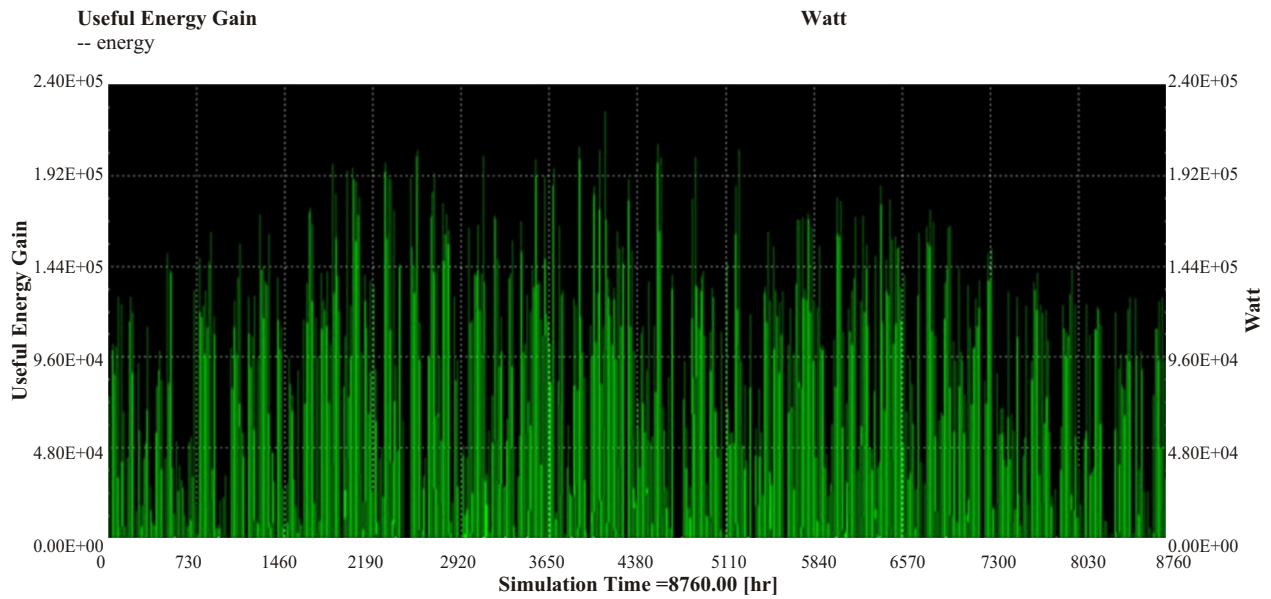-- energy

Fig. 6. Useful Energy Gain of HTF (TRNSYS Simulation)

If we keep mass flow rate of HTF a constant (treating mass flow rate as a constant input and making HTF outlet temperature an output), then the HTF outlet temperature variation can be observed as in Fig 7. The graph also shows the peak value during mid of the summer and shows the variations throughout the year with changing ambient temperature and solar irradiance.

HTF Outlet Temperature   **Centigrade**
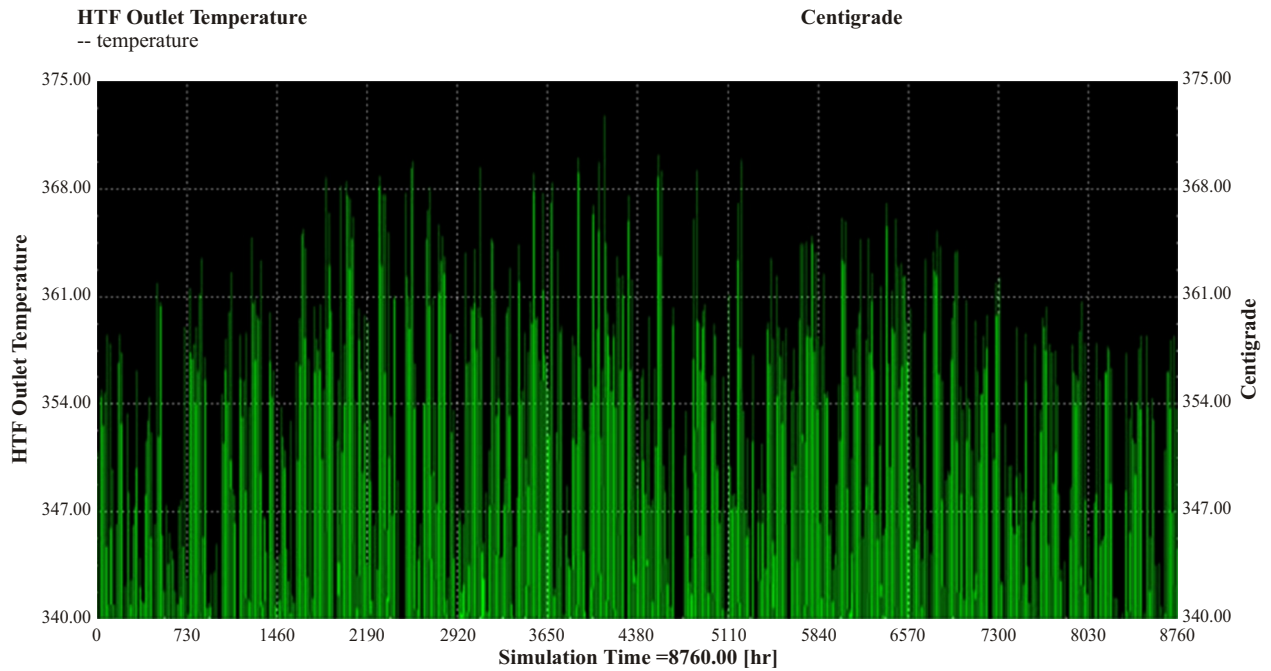-- temperature

Fig. 7. HTF Outlet Temperature (TRNSYS Simulation)

The graph of optical efficiency is a straight line which gives a constant value of 0.764 (see Fig. 8). The value is a constant because the optical efficiency depends upon the optical properties of materials involved.
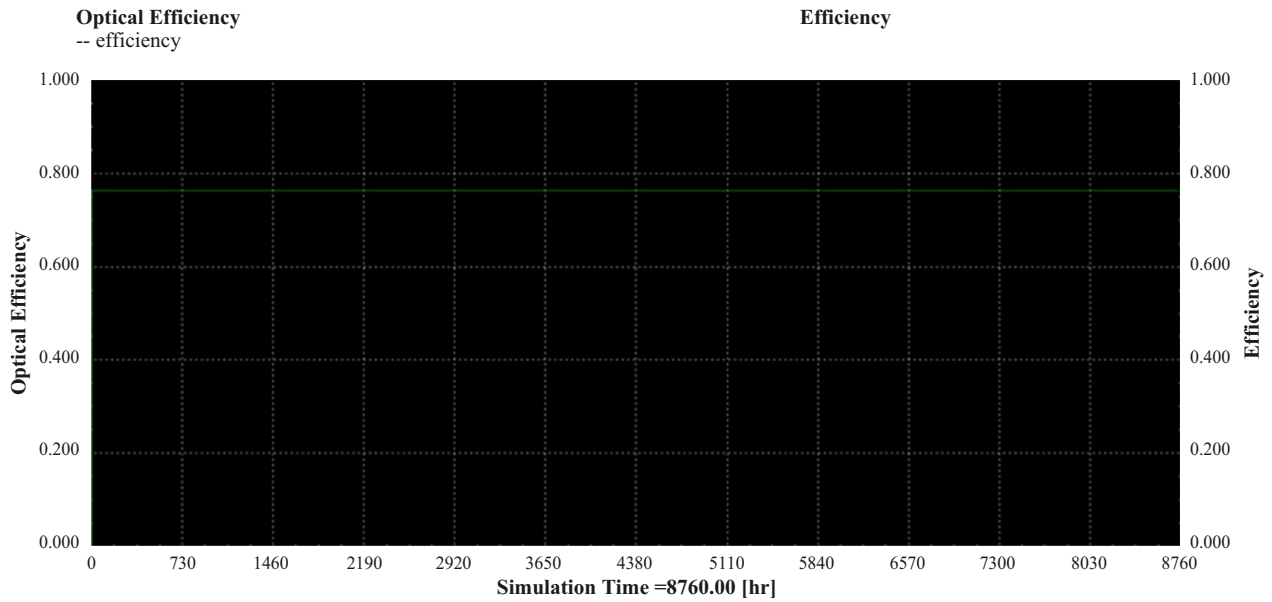

Fig. 8. Optical Efficiency (TRNSYS Simulation)

Thermal efficiency has been plotted two times. Fig. 9 shows its variation for a period of 2 days. The day starts at 1848th hours. For the first few hours the value is zero as solar radiation is zero (night time) or very low (early morning). As the day progresses the value starts increasing and reaches its peak near the mid of the day. It then starts decreasing until it becomes zero in the late evening. If we plot Thermal Efficiency for 8760 hours then the curves are pushed together and the graph looks like Fig. 10.
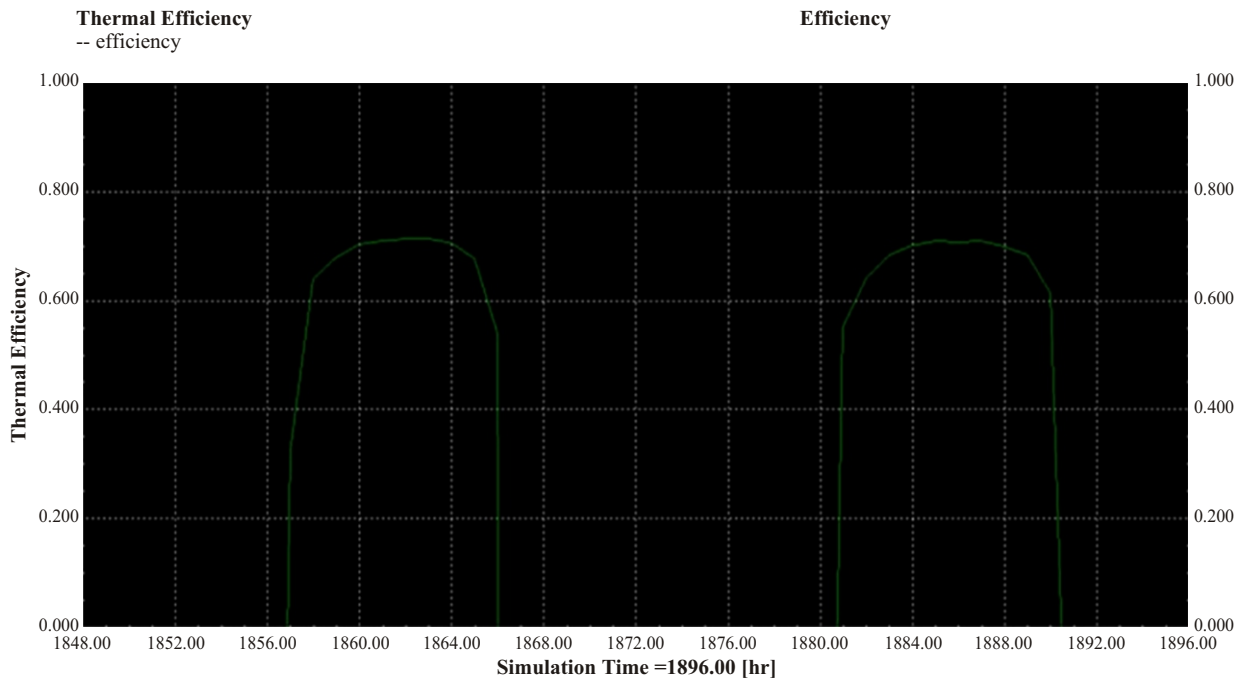

Fig. 9. Thermal Efficiency plotted for 2 Days (TRNSYS Simulation)

Thermal Efficiency
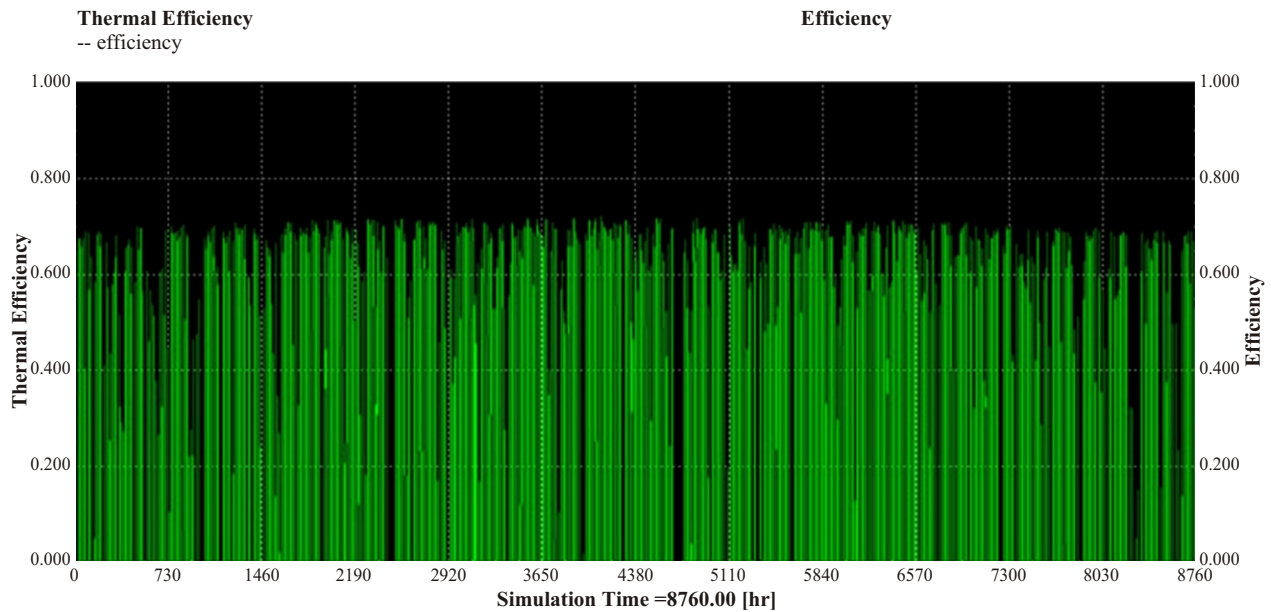-- efficiency

Efficiency

Fig. 10. Thermal Efficiency plotted for One Year (TRNSYS Simulation)

The peak values of the outputs obtained from simulation are given in Fig 5. On the basis of this analysis the performance of the proposed design/plant can be predicted.

TABLE V
SUMMARY OF TRNSYS SIMULATION RESULTS
(PEAK VALUES)

TRNSYS Simulation Result	Parameter	Value
Peak Values	Solar Irradiance	900W/m^2
	Actual Flux absorbed in the Receiver	688 W/m^2
	Useful Energy Gain	226 kW
	HTF Inlet Temperature	340 °C
	HTF Outlet Temperature*	373°C
	HTF Mass Flow Rate	0.00325 kg/sec
	Optical Efficiency	76.4%
	Thermal Efficiency	71.5 %

*Its graphical value can be obtained only if mass flow rate is kept constant.

VII. CONCLUSION

In the present study, a 20kW parabolic trough collector system is designed and its analysis is done on TRNSYS by creating a solar field model. The simulation predicts its performance under changing weather conditions of Lahore that are encountered in a year. The model can also be used for a different design by just varying the values of parameters associated with parabolic trough which can easily be done in TRNSYS Simulation Studio. The TRNSYS model can even be used for simulating the performance of a parabolic trough field located at an entirely different site under different weather conditions by just using the weather data of that site. The data is readily provided by TRNSYS Type 109-TMY2.

The comparison of theoretical and simulations results further justifies the validation of the TRNSYS Model. . It is thus assured that TRNSYS can be treated as an effective and conformist tool to analyze both the average and transient performance of solar parabolic trough. In this paper, the solar field model is designed from zero but it can be further developed by considering the thermal storage. Also, the whole plant can be modeled on TRNSYS (solar field as well as Power Model) [xiii][xvi].

REFERENCES

[i]   S. A. Kalogirou, (2004).Solar thermal collectors and applications. Progress in Energy and Combustion Science. Vol 30, pp. 231-295. Available: http://www.sciencedirect.com/science/article/pii/S0360128504000103

[ii]   H. Price, E. Lüpfert, D. Kearney, E. Zarza, G Cohen, R. Gee, et al., (2002). Advances in Parabolic Trough Solar Power Technology. J Sol Energy Eng 124 pp. 109-125. Available:http://solarenergyengineering. Asmedigitalcollection.asme.org/article.aspx? Articleid=1456429

[iii]   B. Yang, J. Zhao, W. B. Yao, Q. Zhu, H. Qu,

(2010). Feasibility and Potential of Parabolic Trough Solar Thermal Power Plants in Tibet of China. *Power and Energy Engineering Conference (APPEEC)* Chengdu, China, 28-31 March pp. 1-4.

[iv] A. Thomas (1996).Solar steam generating systems using parabolic trough concentrators. *Energy Conversion and Management Vol.37(2)* pp.21545.
Available: http://www.sciencedirect.com/science/article/pii/0196890495001627

[v] M. Eck, E. Zarza, M. Eickhoff, J. Rheinländer, L. Valenzuela, (2003). Applied research concerning the direct steam generation in parabolic troughs. *Solar Energy Vol.74* pp.341-51.
Available: http://www.sciencedirect.com/science/article/pii/S0038092X03001117

[vi] E. Zarza, L. Valenzuela , J. León, K. Hennecke, K. Eck, H. D. Weyers , et al.(2004). Direct steam generation in parabolic troughs: Final results and conclusions of the DISS project. *Energy Vol.29* pp. 635-644.
Available: www.science**direct**.com/science/article/pii/S0360544203001725

[vi] L. Valenzuela, E. Zarza, M. Berenguel, E. F. Camacho (2004). Direct steam generation in solar boilers. *IEEE Control Systems Vol. 24(2)* pp.15-29.
Available: http://ieeexplore.ieee.org/xpl/login.Jsp?tp=&arnumber=1275429&url=http%3A%2F%2Fieeexplore.ieee.org%2Fiel5%2F37%2F28539%2F01275429

[viii] L. Valenzuela, E. Zarza, M. Berenguel, E. F. Camacho (2005). Control scheme for direct steam generation in parabolic troughs. *Solar Energy Vol.78* pp.301-311.
Available: http://www.sciencedirect.com/science/article/pii/S0038092X04001148

[ix] Y. Taitel, O. Shoham, J. P. Brill (1989). Simplified transient solution and simulation of two-phase flow in pipelines. *Chemical Engineering Science Vol.44 (6)* pp.1353-1359.
Available: http://www.sciencedirect.com/science/article/pii/0009250989850080

[x] S. Natan, D. Barnea, Y. Taitel.(2003). Direct steam generation in parallel pipes. *International Journal of Multiphase Flow Vol.29* pp.1669-1683.
Available: http://www.sciencedirect.com/science/article/pii/S0301932203001423

[xi] V. Dudley, G. Kolb, M. Sloan, D. Kearney,(1994). SEGS LS2 solar collector - test results, Report of Sandia National Laboratories, SANDIA94-1884, USA.
Available: http://www.nrel.gov/csp/troughnet/pdfs/segs_ls2_solar_collector.pdf

[xii] M. Mesfin and A. Assefa,(2010). Modeling, Simulation and Performance Evaluation Of Parabolic Trough - Solar Collector Power Generation System. *Journal of EEA,* Vol. 27, pp. 81-89.
Available:https://www.scribd.com/doc/228227779/Modeling-Simulation-and-Performance-Evaluation-of-Parabolic-Trough

[xiii] D. Sauceda, N. Velázquez, O. G. Valladares and R. Beltrán, (2011). Numerical simulation and design of a parabolic trough solar collector used as a direct generator in a solar-GAX cooling cycle. *Journal of Mechanical Science and Technology Vol.25 Issue 6.* Pp.1399-1408.
Available: http://link.springer.com/article/10.1007%2Fs12206-011-0326-y

[xiv] F. Lippek,(1995).Simulation of the Part Load behaviour of a 30MWe SEGS plant, Prepared for Sandia National Laboratories, Albuquerque, NM, SAND95-1293.
Available: http://www.researchgate.net/publication/261483350_Design_of_parabolic_trough_collector_solar_field_for_future_solar_thermal_power_plants_in_Algeria

[xv] S. A. Jones, R. P. Paal, P. Schwarzboezl, N. Blair and R. Cable (2001). Trnsys Modeling of The SEGS Vi Parabolic Trough Solar Electric Generating System. *Proceedings of Solar Forum 2001: Solar Energy: The Power to Choose.*
Available: http://elib.dlr.de/46330/1/SEGSVI_Modelling_Article.pdf

[xvi] B. Zeroual and A. Moummi, (2012). Design of Parabolic Trough Collector Solar Field for Future Solar Thermal Power Plants in Algeria. *Proceedings of the 2nd International Symposium on Environment-Friendly Energies and Applications, Northumbria University.* pp. 168-172.
Available:http://ieeexplore.ieee.org/xpl/abstractAuthors.jsp?reload=true&arnumber=6294069

[xvii] M. Kummert,(2013). Introduction to TRNSYS. *MEC 4000 Presentation.*

NOMENCLATURE

A = area (m^2)
Cp = specific heat (kJ/kg.K)
G = solar irradiance (W/m^2)
L = factor related to end losses
Lu = land usage factor
m = mass flow rate (kg/sec)
M = incidence angle modifier
n = number of collectors
Q = Heat Transfer (W)
S = shading factor
ΔT = temperature difference (w.rt ambient)
W = width of the collector (m)

SUBSCRIPTS

aperture = aperture of collector
c = Collector
field = solar field
HTF = heat transfer fluid
i = incidence
SCA = solar collector assembly
spacing = space between collector arrays
u = useful
z = zenith

GREEK SYMBOLS

α = absorptivity
ρ = reflectivity
τ = transmissivity
$\square$ = intercept factor
$\square$ = angle
$\square$ = efficiency