Performance evaluation of hybrid solar parabolic trough concentrator systems in Hong Kong

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Abstract

In hybrid parabolic trough collector system, photovoltaic cells are also installed on the receiver pipes, here the solar energy is directly converted to electrical energy by the photovoltaic cells. The working fluid circulating in the receiver pipes is for solar thermal purpose as well as to cool down the temperature of solar cells, hence maintaining is conversion efficiency. Therefore a hybrid parabolic trough collect system is making full use of the energy spectrum of solar radiation both the visible light and its thermal part. The overall yield of the system is increased and therefore the energy yield per unit capital cost is reduced. There are a number of studies on parabolic trough solar thermal systems or parabolic trough photovoltaic systems, however not much has been done on hybrid solar parabolic trough concentrator systems.

The purpose of this paper is to develop a mathematical model for hybrid solar parabolic trough concentrator (PTC) systems. The model is for estimation of energy outputs, losses and efficiencies of various parts of the system when the system is operating under different climate condition, various operating conditions, diverse system configurations and a range of loading conditions. These sub-systems are modelled separately and then the models are integrated into one model and simulated by one computer program with user-friendly interface. The model is then tested by the software using Hong Kong's climatic conditions and its performance is evaluated. for Hong Kong and other densely populated city with sub-tropical climatic conditions in southern part of China. The results are important to promote this application in these areas.

1 INTRODUCTION

The main aim of this paper is to present the work on developing a mathematical model and the simulated results for performance of hybrid solar parabolic trough concentrator systems (PTC) under Hong Kong's climatic conditions. The model is for estimation of energy outputs, losses and efficiencies of various parts of the system, when the system is operating under different climate condition, various operating situations, diverse system configurations and a range of loading conditions. Then Hong Kong's climatic conditions parameters are used to test its performance.

2 BACKGROUND

The parabolic trough is one of the most advanced concentrator systems for solar energy. This technology is used in the largest grid connected solar-thermal power plants in the world. One such complex in the U.S. that uses parabolic troughs is the Kramer Junction companies that operate and maintain five 30-megawatt Solar Electric Generating Systems (SEGS) which comprise 150 to 354 megawatts of installed parabolic trough solar thermal electric generating capacity located in California's Mojave Desert.

A parabolic trough collector (PTC) has a linear parabolic-shaped reflector that focuses the sun's radiation on a linear receiver located at the focus of the parabola. The collector tracks the sun along one axis from east to west during the day to ensure that the sun is continuously focused on the receiver pipes. Because of its parabolic shape, a trough can focus the sun at 30 to 100 times its normal intensity (concentration ratio, CR) on a receiver pipe located along the focal line of the trough.

A collector field consists of a large field of single-axis tracking parabolic trough collectors. The solar field is modular in nature and is composed of many parallel rows of solar collectors aligned on north-south horizontal axis. A working (heat transfer) fluid is heated as it circulates through the receivers and returns to a series of heat exchangers at a central location where the fluid is used to generate high-pressure superheated steam, or hot water depends on the working temperature of the fluid.

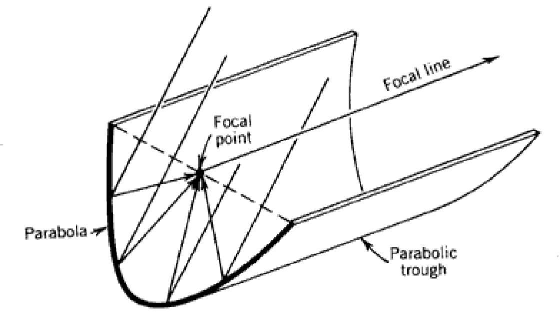

Figure 1 A parabolic trough

In a hybrid PTC system, photovoltaic (PV) cells are also installed on the receiver pipes. Here the solar energy is directly converted to electrical energy by the photovoltaic cells. The working fluid circulating in the receiver pipes is for solar thermal purpose as well as to cool down the temperature of solar cells and hence maintaining the conversion efficiency of the solar cell at a reasonable level. Therefore a hybrid PTC system is making full use of the energy spectrum of solar radiation both the visible light and the thermal part of it. There are a number of studies on parabolic trough solar thermal systems or PTC photovoltaic systems, however not much have been done on hybrid solar parabolic trough concentrator systems. The research work will focus on small scale systems in the order of tens to hundreds of kilowatt, which has a more practical application in densely populated city such as Hong Kong.

3 METHODOLGOY

A hybrid solar PTC system can be divided into several key subsystems: the parabolic troughs, the solar tracking control system, the photovoltaic cells, electrical connection system, the grid-connected inverter, the receiver pipes, the pipe connection system and the heat exchange systems. The research will develop mathematical model and simulation programs of each of these subsystems and then integrate them together to form a comprehensive model and simulation package, as shown in Figure 2. This paper will have more focus on the electrical aspect of the system, with few details on the solar thermal side which is the second part of the whole research.

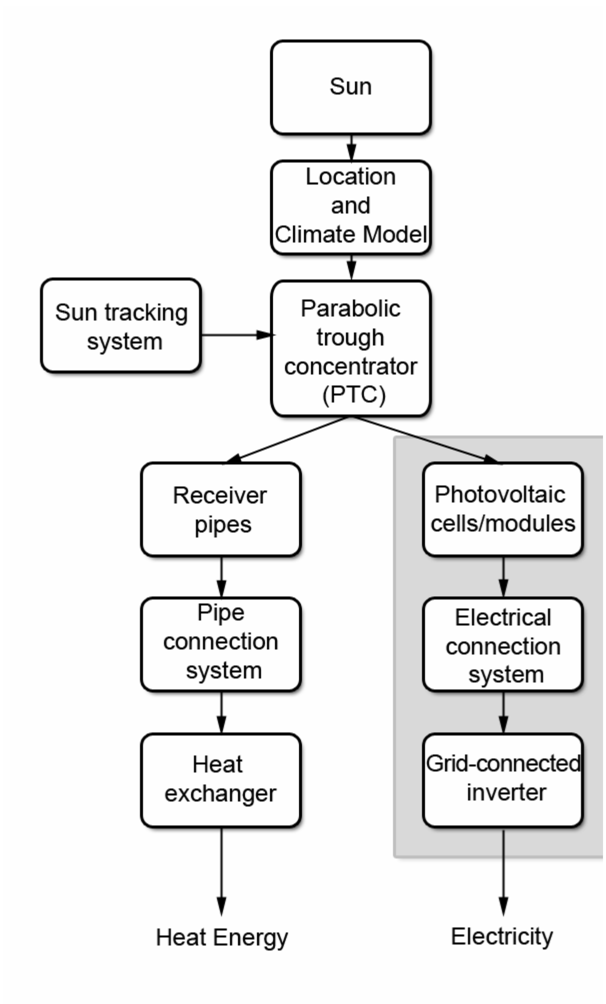

Figure 2 Structure of hybrid PTC simulation software

3.1 Climate model

The climate condition is modelled by weather data from Hong Kong Observatory. Here a short-term weather database for the year 1997-2001 is used instead of a long-term (1960-1990) one because it was found that the annual solar energy received in Hong Kong has decreased by 13% [1] and the distribution profile across seasons has changed due to increase of atmospheric aerosols that scatter the incoming solar radiation [2].

3.2 PTC

For the parabolic trough, ray-tracing technique for non-imaging applications, together with the algorithm on calculation of the sun position, is used to determine the radiation energy falling on the receiver pipes/PV modules of the system.

3.3 Photovoltaic cells/modules

For the photovoltaic cells/modules, the cell current-voltage (IV) curves are modelled using a lumped parameter, two-diode equivalent circuit that includes a model for reverse voltage breakdown. Parameters used include short circuit current, open-circuit voltage, cell temperature and solar irradiance.

3.4 Electrical connection system

For the electrical connection system, the modelling is a complex electrical circuit analysis within multiple DC sources and distributed resistive elements, hence the losses in the wires can be calculated under various cases of source voltages and flow patterns of load currents. Finally the power at the input of the inverter can be found.

3.5 Grid-connected inverter

In this research, grid-connected inverter is assumed to eliminate the necessities of a battery storage system and reducing the system cost. Therefore a grid-connected inverter is required to be installed in the system. The inverter is modelled by parameters such as power input, nominal power and conversion efficiency.

The modelling of modules discussed in 3.1, 3.3, 3.4 and 3.5 (indicated in shaded parts of Figure 1) is based on the work done by the author as discussed in previous papers [3].

3.5 Receiver pipes

It is the heat-collecting element in which the heat transfer fluid flows. A glass envelope (with PV on it) covers the receiver pipe, which is assumed to have no radial temperature gradients.

3.6 The pipe connection system

It is treated in the similar way as the electrical systems, mainly to find out the losses in the flow of the heat transfer fluid, and hence determine the heat power output at the end of the pipe connection system.

3.7 Heat exchanger

Its effectiveness and heat transfer coefficients are a function of water mass flow rate and water temperature at the inlet of the exchanger. Standard steady state model will be adopted, as it should be of sufficient accuracy level for the study.

After each subsystem is modelled, they are integrated into one model and simulated by a computer program. In this research the programming language used is LabVIEW V7.1 which is a popular programming language used in engineering calculations, control and simulations. Given a set of system parameters, the instantaneous power at various part of the system can be found. Continuous simulation for a given period time can give an indication of annual electrical and thermal energy yield.

4 SIMULATION MODEL

In this research, modelling of PTC is based on the work by Kalogirou [5] with a number of critical parameters such as rim angle and optical efficiency. With slight modifications a hypothetical model of hybrid PTC has been proposed to roughly estimate its electrical performance in Hong Kong's climatic conditions. The parameters are listed below. Refer to Figure 3 for details.

Collector aperture	A_c	=	4m
Focal length	f	=	1m
Rim angle	ϕ_r	=	90^o
Collector length	L	=	6.465m
Optical efficiency	n_o	=	0.642
Receiver aperture	A_r	=	0.329m
Concentration ratio	CR	=	11.15

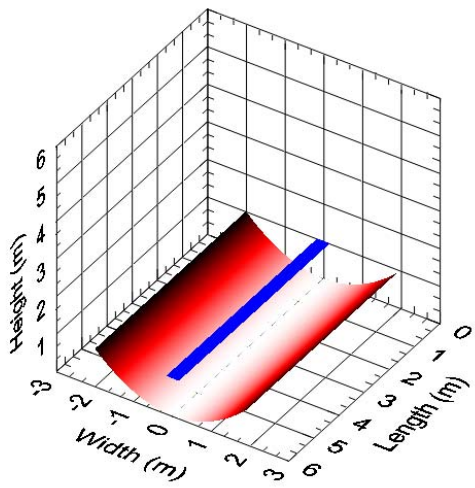

Figure 3 hypothetical model of a hybrid PTC

Notice that slight modifications have been done on traditional PTC systems. A row of PV modules (shown by the rectangular shape above the PTC) facing downward acts as the receiver and receiver pipes are installed at the back (top) of the PV modules. Since the PV modules are not cylindrical shape therefore they are installed slightly below the focus in order to avoid optical short-circuit. The rim angle is chosen in a way such that all energy reflected can be absorbed by PV modules. The parameters for electrical system are listed below:

PV modules	5 nos. Copper Indium Diselenide (CIS) modules
Operating voltage	$83V_{DC}$
STC Power	200W
Inverter nominal power	2.5kW
Inverter peak efficiency	94%

The PV modules are connected in series. Characteristics of PV modules and inverter chosen in the simulations have been studied by Lam [6] [7] in detail and their performances were investigated thoroughly. As a first trial we have chosen proprietary instead of custom-made PV cells because proprietary modules are of lower cost and can be assembled easily when it will be actually built in the next stage of this research.

The system working temperature has been set to maximum 50°C which is a typical value for solar thermal system. This also helps to reduce average working temperature of PV modules and thus increases efficiency.

5 RESULTS OF SIMULATIONS

Annual electrical energy yield of the hybrid PTC system is shown below.

Table 1 Simulation 1: annual electrical energy yield of the hybrid PTC, the system yield is the electrical energy obtained after passing through the inverter.

Month	PV Yield	System Yield	Solar Energy
JAN	207.34kWh	191.71kWh	1876.33kWh
FEB	213.69	197.28	1918.82
MAR	230.18	211.81	2093.49
APR	205.52	187.37	1890.94
MAY	265.47	243.97	2424.67
JUN	261.37	239.78	2386.79
JUL	313.25	288.55	2832.53
AUG	304.80	281.26	2763.38
SEP	283.52	261.93	2570.08
OCT	268.20	247.94	2441.91
NOV	247.37	228.92	2244.49
DEC	228.98	211.87	2064.77
Total	3029.67	2792.39	27508.20
Inverter Efficiency		92.17%	
System Efficiency		10.15%	

Theoretically the difference, which is about 20000kWh, between system yield and solar energy received is available for the thermal sub-system of this hybrid PTC to produce hot water. Notice that this is only the maximum value and thermal system losses should be considered in later stage in order to find the real amount of heat energy available.

To understand how the thermal sub-system can help increasing the performance of the electrical sub-system, another simulation has been done by removing the thermal sub-system while keeping the same parameters.

Table 2 Simulation 2: annual electrical energy yield of the hybrid PTC without maximum working temperature

Month	PV Yield	System Yield	Solar Energy
JAN	207.06kWh	191.45kWh	1873.94kWh
FEB	212.31	196.00	1916.3
MAR	224.92	206.90	2090.83
APR	195.94	178.4	1888.54
MAY	249.31	228.89	2421.59
JUN	241.07	220.83	2383.76
JUL	287.63	264.63	2828.93
AUG	282.22	260.18	2759.87
SEP	266.1	245.66	2566.82
OCT	256.48	237.00	2438.81
NOV	243.11	224.94	2241.64
DEC	228.49	211.42	2062.14
Total	2894.70	2666.38	27473.33
Inverter Efficiency		92.12%	
System Efficiency		9.71%	

5 DISCUSSIONS

From the two simulations it is noticed that the system efficiency has increased from 9.71% to 10.15% and an extra 130kWh of electricity has been generated, also the heat energy is not wasted with the thermal system installed.

From the figures listed above one may argue that further decrease of maximum working temperature can increase system efficiency, however this may decrease efficiency of the thermal system. Finding the maximum of total of electrical and thermal system output may not be the best solution for such installations in Hong Kong since the local demand for electricity is much higher than that of hot water. Therefore one should carefully consider the balance between outputs of electrical and thermal system before an optimization is made.

Notice that most of the parameters used in the simulation may not necessarily be the optimum values. For example, difference between system yield of simulation 1 and 2 can be further increased by increasing CR and using more efficient PV cells. Since a hybrid PTC system has added complexity to a traditional one (either PV or solar thermal only), therefore to design an optimum system there is need to run more simulations using different sets of parameters. Intelligent algorithms such as Genetic Algorithm should be used to reduce time consumption in finding out the optimum parameters in future.

In a later simulation using an efficiency model for CIS modules based on the work done by Lam [5] it is found that electricity output is much lower than the values given in this paper. Although the model accurately estimates the performance of CIS modules, the model did not include any experimental data taken at solar irradiance above $1000Wm^{-2}$. Therefore considerations should be taken to accurately evaluate PV module performance in this range.

Whether high-efficiency, custom-made PV cells should be replaced with proprietary PV modules of low-efficiency is also questionable. As discussed above, situations in a densely populated city with sub-tropical climate such as Hong Kong where there is high demand of electricity there is always an advantage for any renewable energy system to generate more electricity than hot water while maintaining a relatively low cost. More simulations in later stage of this research should be done on evaluating the system performance with high-efficiency PV cells or modules.

6 CONCLUSIONS

In this research we have been developing a model for evaluating a hybrid PTC system. Initial simulations have been done to roughly estimate how the electrical sub-system of such a hybrid system would perform in sub-tropical climatic conditions. It is believed by using a hybrid PTC system that recovers heat energy the overall effectiveness of the system, in terms of both heat and electrical energy, can be increased and hence reduces payback period. The results presented here are not optimized and it is anticipated that optimized results and parameters can be produced after the thermal sub-system is modelled. However it is anticipated that due to higher ambient temperature in Hong Kong's urban area it would be quite effective to extract more heat energy by this system which can be improved further by optimization.

7 ACKNOWLEDGEMENTS

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