SOLAR PARABOLIC TROUGH COLLECTOR AND THEIR APPLICATIONS

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***ABSTRACT*:** *As the world struggles with the energy and environmental crisis, there is an urgent need to develop and promote environmentally benign technologies based on sustainable energy sources. Solar energy is the cheapest and widely available renewable energy source that matches the different applications. This paper presents an overview of the parabolic-trough collectors that have been built and marketed during the past century, as well as the prototypes currently under development. It also presents a survey of systems which could incorporate this type of concentrating solar system to supply thermal energy up to 400˚C, which includes solar thermal power plants, domestic hot water and space heating, solar air-conditioning and refrigeration, industrial process heating, solar desalination system, solar water pumping system, chemistry applications etc.*

Keywords—Parabolic Trough Collector, Renewable Energy, Solar Collector, Solar Energy Applications

I: INTRODUCTION

Solar collectors are special kind of heat exchangers that transform solar energy into internal energy of the transport medium. It is a device which absorbs the incoming solar radiation, converts it into heat, and transfers this heat to a fluid (usually air, water or oil) flowing through the collector. The solar energy thus collected is carried from the circulating fluid either directly to the hot water or space conditioning equipment or to a thermal energy storage tank from which can be drawn for use at night and/or cloudy days.

There are basically two types of solar collectors: non-concentrating (or stationary) and concentrating. A non-concentrating collector has the same area for intercepting and for absorbing solar radiation; e.g. flat plate collector, compound parabolic collector, evacuated tube collector etc. Whereas a sun-tracking concentrating solar collector usually has concave reflecting surfaces to intercept and focus the sunꞌs beam radiation to a smaller receiving area, thereby increasing the radiation flux; e.g. parabolic trough collector (PTC), linear Fresnel reflector, parabolic dish reflector, heliostat field collector etc [1].

The PTC is composed of a parabolic-trough-shaped concentrator that reflects direct solar radiation onto a receiver tube located in the focal line of the parabola (linear-focus concentration). Since the collector aperture area is bigger than the outer surface of the receiver tube, the direct solar radiation is concentrated. The concentrated radiation reaching the receiver tube heats the fluid that circulates through it, thus transforming the solar radiation into thermal energy in the form of sensible heat of the fluid. The configuration of typical PTC is shown in Figure 1 [2].

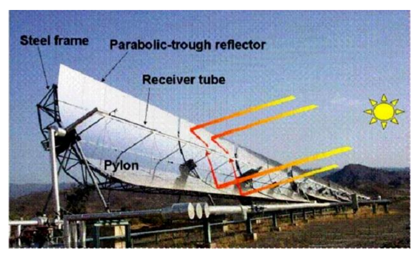

Fig. 1 Typical Parabolic Trough Collector

The comparison of various concentrating collectors is given in Table 1 [1, 3].

Table 1: Comparison of various concentrating collectors

Collector Type	PTC	Linear Fresnel	Parabo-lic dish	Heliostat collector
Thermal efficiency	Low	Low	High	High
Temp. Range (°C)	50-400	50-300	150-1500	300-2000
Relative cost	Low	Very low	Very high	High
Concentra-tion ratio	15-45	10-40	100-1000	150-1500
Technology	Very mature	Mature	Recent	Most recent
Tracking	1-axis	1-axis	2-axis	2-axis

PTC applications can be divided into two main groups. The first and most important is Concentrated Solar Power (CSP) plants. There are currently several commercial collectors for such applications that have been successfully tested under real operating conditions. Typical aperture widths are about 6 m, total lengths are from 100 to 150 m, geometrical concentrating ratios are between 20 & 30 and temperatures are from 300 to 400 °C. The other group of applications requires temperatures between 100 & 250 °C. These applications are mainly industrial process heat (IPH), low-temperature heat demand with high consumption rates (domestic hot water (DHW), space heating and swimming pool heating), pumping irrigation water, desalination and heat-driven refrigeration and cooling. Typical aperture widths are between 1 & 3 m, total lengths vary between 2 & 10 m and geometrical concentrating ratios are between 15 & 20 [4].

This paper reviews the applications of PTCs in various systems to supply thermal energy up to 400°C, which includes solar thermal power plants, domestic hot water and space heating, solar air-conditioning and refrigeration, industrial process heating, solar desalination system, solar water pumping system, chemistry applications etc. The developments carried out in PTCs are also presented.

II: APPLICATIONS OF PTCs

1) <u>Solar Thermal Power Plant</u>:

There are two ways to integrate a solar energy using PTCs in a steam turbine power plants, directly, *by generating steam in the solar field*, or indirectly, *by heating thermal oil in the solar field and using it to generate steam in a heat exchanger*. In both cases, solar fields can drive all types of steam turbines. Many investigators have developed and analyzed the performance of solar thermal power plant using PTCs. The typical layout of solar thermal power plant is shown in Figure 2 [1].

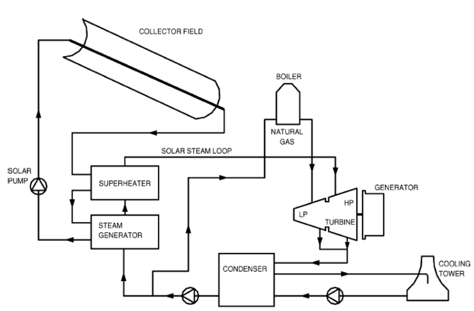

Fig. 2 Typical Layout of Solar Thermal Power Plant

J. Birnbaum et al. [5] discussed the integration concept of a thermal storage system into the overall plant as one important difference between indirect steam generation (ISG) and direct steam generation (DSG) parabolic trough power plants. Because of the characteristics of the phase change material (PCM) storage, the superheated steam generated was at a lower pressure as compared to the main steam from the solar field. It has been shown that feeding the steam from the storage into the main path of the HP turbine (first stage) results in best integration and performance. Compared to other concepts for reheating the steam, heating with condensing main steam turns out to be best. It doesn't improve the performance, but is needed to avoid unacceptable moisture in the LP turbine. They compared the performance of PTCs at 400 °C and 500 °C configurations in terms of electricity yield as shown in Figure 3.

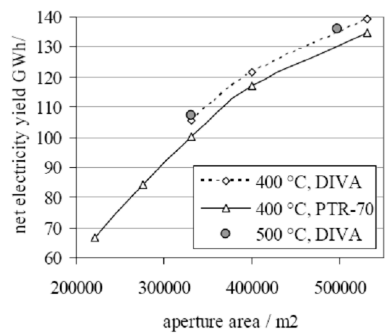

Fig. 3 Electricity Yield with 400 °C and 500 °C Configurations

I. Purohit and P. Purohit [6] carried out the techno-economic evaluation of concentrating solar power (CSP) technologies at several Indian locations. To analyse the financial feasibility of CSP technologies in Indian conditions two projects namely PS-10 (based on power tower technology) and ANDASOL-1 (based on PTC technology) have been simulated at several Indian locations. They found that internalization of CDM benefits further improve the values of financial performance indicators of CSP systems and the use of these systems is financially feasible for the locations in Rajasthan, Gujarat (Bhuj, Ahmedabad, Rajkot), Madhya Pradesh (Gwalior, Bhopal) and Leh in Jammu and Kashmir thus providing opportunity for large-scale dissemination of CSP systems in these locations.

2) <u>Domestic Hot Water And Space Heating:</u>

One of the most widespread applications of solar thermal energy is hot water production. According to an IEA report for 2006, solar thermal collector capacity in operation worldwide was about 127.8 GWth (182.5 millions m^2), *most of it is domestic*, both for DHW (kitchen, shower, laundry and sanitation facilities) and space heating [7].

U. Frei and P. Vogelsanger [8] carried out experimental investigations on the combined solar hot water and space heating systems. Especially for small combined systems with typical solar fractions of 20 to 30%, a potential for further improvement is detectable. Most of the current developments of advanced DHW-systems are trying to make the system more cost effective. One example is to improve the degree of integration to reduce installation costs or to cooperate with other manufacturers to increase production volume by strategic alliances. Similar activities might be observed for combined-systems.

T. Collins and S. Parker [9] enumerated the applications of DHW and space heating for large buildings; such as industrial buildings, factories, hospitals, educational centres, sport facilities, government buildings, prisons, airports, bus and train stations, etc. In most situations, a minimum hot water consumption of about 1900 lit/day would be needed to make a PTC system feasible for large scale water heating plants.

3) Solar Air-Conditioning And Refrigeration:

Solar absorption cooling systems have become more attractive because the maximum cooling load occurs when the most solar radiations are available. Conventional solar absorption cooling systems are commonly comprised of a solar collector, a storage tank and an absorption cooling chiller. The main components of an absorption chiller include four heat exchangers e.g. generator, condenser, evaporator and absorber. Many investigators have used PTCs for solar air-conditioning and refrigeration systems.

I. Haim et al. [10] performed a simulation and analysis of two open-cycle absorption systems. Both systems comprise a closed absorber and evaporator as in conventional single stage chillers. The open part of the cycle is the regenerator, used to reconcentrate the absorber solution by means of solar energy. The analysis was performed with a computer code developed for modular simulation of absorption systems under varying cycle configurations (open- and closed-cycle systems) and with different working fluids. Based on the specified design features, the code calculates the operating parameters in each system. Results indicate a definite performance advantage of the direct-regeneration system over the indirect one.

M. Hawlader et al. [11] developed a lithium bromide absorption cooling system employing an 11x11 m^2 collector/regenerator unit. A computer model has been developed which was validated against real experimental values with good agreement. The experimental results showed a regeneration efficiency varying between 38 and 67% and the corresponding cooling capacities ranged from 31 to 72 kW.

M. Mazloumi et al. [12] carried out experimental investigations on solar single effect lithium bromide water absorption cooling system. The solar energy was absorbed by a horizontal N-S parabolic trough collector and stored in an insulated thermal storage tank. The system has been designed to supply the cooling load of a typical house where the cooling load peak is about 17.5 kW (5 tons of refrigeration), which occurs in July. A thermodynamic model has been used to simulate the absorption cycle. The results showed that the collector mass flow rate has a negligible effect on the minimum required collector area, but it has a significant effect on the optimum capacity of the storage tank. The minimum required collector area was about 59.8 m^2 for the collector mass flow rate of 1800 kg/h with the initial temperature of the storage tank equal to ambient temperature during sunshine hours of the design day for July. The operation of the system has also been considered after sunset by saving solar energy. A schematic diagram of solar absorption cooling system is as shown in Figure 4.

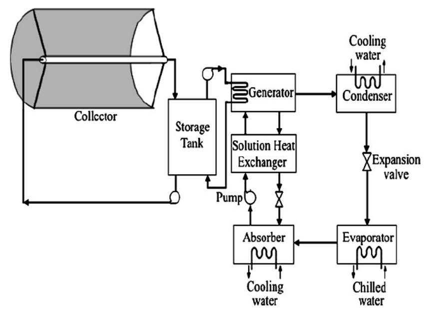

Fig. 4 PTC with Absorption Cooling System

N. Ghaddar et al. [13] presented modelling and simulation of a solar absorption system. The results showed that, for each ton of refrigeration, it is required to have a minimum collector area of 23.3 m^2 with an optimum water storage capacity ranging from 1000 to 1500 l, for the system to operate solely on solar energy for about 7 hr per day. The economic analysis performed showed that the solar cooling system is marginally competitive only when it is combined with domestic water heating.

4) Industrial Process Heat (IPH):

Of the total energy used by industry, a major portion approximately 45–65% is used for direct application of industrial process heat in the preparation and treatment of goods. Hence, there exist wide scopes of using PTCs in IPH.

4.1. Solar steam generation systems

A. Thomas [14] presented the various aspects of solar steam generating systems and the operational problems that were encountered by various users of these systems. According to the latest IEA statistics (for 2006), industry is one of the major consumers of energy worldwide-around 30%. In 2007, there were about 90 operating IPH solar thermal plants with a total capacity of about 25 MWth (35,000 m^2) worldwide. The key sectors are food and beverages including wine, textile, transport equipment, metal and plastic treatment, and chemicals. And the most suitable processes are cleaning, drying, evaporation and distillation, blanching, pasteurisation, sterilisation, cooking, melting, painting, and surface treatment. The thermal energy demand for IPH is below 300 °C, and about 37% of the total IPH demand is in the range of 92–204 °C. According to the ECOHEATCOOL study done in 32 countries, 27% of the thermal energy demand for IPH is between 100ï 400 ęC. For that reason, one of the most important applications of a small-sized PTC is IPH.

4.2 Solar industrial air and water systems

S. Kalogirou [15] investigated the viability of using PTC for industrial heat generation in Cyprus. The system was analyzed both thermally and economically in order to show the magnitude of the expected benefits. The system was used to deliver 2000 kg/h of hot water at 85 °C for the first three quarters of each hour from 8:00ï 16:00 hrs, 5 days a week. The system consisted of an array of PTC, hot water storage tank, piping and controls. The optimum collector area was 300 m², flow rate was 54 kg/m² h and the storage tank size was 25 m^3. The system covers 50% of the annual load of the system and gives life cycle savings of about 5 lacs. The EïW tracking system (collector axis aligned in NïS direction) was found to be superior to the NïS one. It was found that bigger the load the bigger the collector area required, the greater the first year fuel savings and the greater the life cycle savings of the installation. Based on the study it was concluded that, it is more viable to apply solar PTC industrial process heat to higher energy consumption industries.

J. Gosselar and M. Johnson [16] categorized IPH needs into three main temperature ranges which can be achieved with solar energy. The lowest temperature range consists of temperature below 80°C. Solar collectors are capable of meeting these temperatures and are commercially available today. The medium temperature category is between 80°C and 250°C. While the collectors servicing this level of heat demand are relatively limited, they do exist and are on the verge of emerging into competitive commercial production. The highest range includes temperature over 250°C and requires concentrated solar power (CSP) to achieve such temperatures. While CSP furnaces are rareð a few have been installed world wide for electricity productionð they can achieve temperatures as high as 3500°C. According to a study of industrial heating in European countries, 30 percent of industrial processing requires heat below 100°C and 27 percent of industrial heating needs can be met with heat between 100-400°C, and 43 percent requires heat over 400 °C. The details of temperature range for different industrial processes are given in Table 2.

Table 2: - Temperature Range for Different Industrial Processes

Industries	Process	Temp. (°C)
Dairy	Pressurization	60-80
	Sterilization	100-120
	Drying	120-180
	Concentrates	60-80
	Boiler feed water	60-90
Tinned food	Sterilization	110-120
	Pasteurization	60-80
	Cooking	70-90
	Bleaching	70-90
Textile	Bleaching, dyeing	60-90
	Drying, degreasing	100-130
	Dyeing	70-90
	Fixing	160-180
	Pressing	80-100
Paper	Cooking, drying	60-80
	Boiler feed water	60-90
	Bleaching	130-150
Chemical	Soaps	200-260
	Synthetic rubber	150-200
	Processing heat	120-180
	Pre-heating water	60-90
Meat	Washing, sterilization	60-90
	Cooking	90-100
Beverages	Washing, sterilization	60-80
	Pasteurization	60-70
Flours & by-products	Sterilization	60-80
Timber by-products	Thermo diffusion -beams	80-100
	Drying	60-100

5) <u>Solar Desalination System:</u>

The importance of supplying potable water can hardly be overstressed. And considering the shortage of water, the only inexhaustible source of water is the ocean. However, its main drawback is the high salinity. It would be attractive to tackle the water-shortage problem with desalination of ocean water, which may be mixed with brackish water to increase the amount of fresh water and reduce the concentration of salts to around 500 ppm [17].

S. Kalogirou [18] analysed the various desalination methods with respect to their primary energy consumption, sea-water treatment requirement and equipment cost and found that the multiple-effect boiling evaporator is the most suitable method for stimulation by solar energy. The modelling has been used to predict the rate of fresh water produced by four sizes of systems, varying from small 10 m^2 to large 2160 m^2 collector area applications. From the economic analysis, it has been reported that PTC desalination system is cost effective and environment friendly. Figure 5 shows the variation of thermal efficiency of various collectors against ratio of temperature difference (æT) and intensity of beam radiation (I). It can be seen that at a temperature of 100 °C, which occurs at a æT/I value of about 0.1, PTCs work at an efficiency of about 62%, CPCs at about 32% and the FPC at about 10%. This clearly suggests that the PTC is the best type of collector for this application.

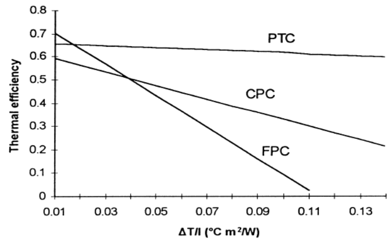

Fig. 5 Typical Collector Performance Curves

A. Scrivani et al. [19] reviewed the applications of PTC for water production, remediation and waste treatment. The various possibilities of using PTCs were identified for clean water production by distillation of sea or brackish water (desalination), by condensation of atmospheric humidity, by distillation of waste water, production of nitrogen and phosphorus for agriculture by waste water distillation etc. It was reported that all the systems described above are low cost, pollution free and alternative to incineration.

H. Qiblawey and F. Banat [20] presented the overview of solar thermal desalination technologies. Solar energy coupled to desalination offers a promising prospect for covering the fundamental needs of power and water in remote regions. Solar desalination can either be direct; *use solar energy to produce distillate directly in the solar collector*, or indirect; *combining conventional desalination techniques, such as multistage flash desalination (MSF), vapor compression (VC), reverse osmosis (RO), membrane distillation (MD) and electrodialysis, with solar collectors for heat generation*. Direct solar desalination compared with the indirect technologies requires large land areas and has a relatively low productivity. It is however competitive to the indirect desalination plants in small-scale production due to its relatively low cost and simplicity.

6) Solar Pumping System:

Solar pumps are of special significance in countries where the farming communities are distributed over large and distant areas and where electrical power is not readily available. This would include most of the countries in Asia, Africa and Latin America [21]. It is mainly a problem of conversion of heat energy available from the sun into mechanical energy. Many investigators have used solar energy for water pumping systems.

Y. Wong and K. Sumathy [22] reviewed the past efforts made to develop solar thermal water pumping systems which employ either conventional pumps or unconventional pumps and emphasize how the system modifications were made to suit different pumping conditions and requirements. The technology continues to develop, and the cost of producing power with solar thermal water pumps is falling. They reported that, if the costs of fossil fuels, transportation, energy conversion, electricity transmission and system maintenance are taken into account; the cost of energy produced by solar thermal water pumps would be much lower than that for electrical water pumps.

S. Talbert et al. [23] developed the world's largest known solar powered irrigation water system as shown in Figure 6. The pump was capable of developing 37 kW and could pump 38000 litres of irrigation water per minute at peak operation. The system consisted of 554 m² of parabolic solar collectors. The power required to drive high volume flow propeller pump was generated through a Rankine cycle using R 113 as the working fluid.

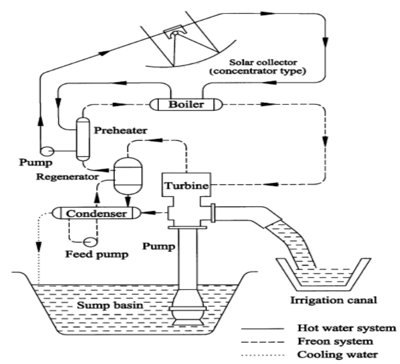

Fig. 6 PTC for Water Pumping System

7) Solar Chemistry

PTCs have also been used by various researchers for various chemical processes. T. Sano et al. [24] analyzed Photocatalytic degradation of volatile organic compounds (VOCs) with Pt-loaded TiO2 at elevated temperatures in the laboratory experiments (40ï 190 °C) and in the field experiments (30ï 230 °C). The temperature of catalyst coated on the sunlight receiver was easily elevated to around 200 °C by PTC (1m X 1m). When gaseous toluene (15 ppm) or acetaldehyde (400 ppm) was passed through the reactor, 79% of toluene or 93% of acetaldehyde was removed continuously. In the similar condition, bare TiO2 was rapidly deactivated by the formation of by-products. The combination of sunlight concentrator and Ptï TiO2 catalyst exhibited the enhancement of complete degradation of VOCs. The view of catalytic reactor with PTC mounted on a two-axis sun tracking mechanism is shown in Figure 7.

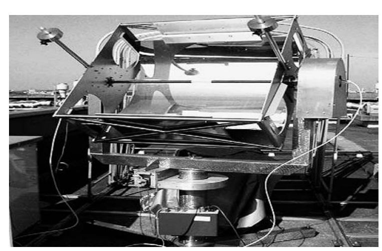

Fig. 7 Catalytic reactor with PTC

A. Thomas and H. Guven [25] investigated the effect of optical errors on the flux distribution around absorber tubes of PTCs using simulation techniques. They found that the total optical error has profound effect on the intercept factor, as well as on the optical efficiency of PTCs.

III: CONCLUSIONS

PTCs found applications in solar thermal power plants, domestic hot water & space heating, solar air-conditioning & refrigeration, industrial process heating, solar desalination system, solar water pumping system, solar furnace, chemistry applications etc. There are many other applications which are not fully developed or are not matured yet.

The application areas described in this review show that solar PTC can be used in a wide variety of systems, could provide significant environmental and financial benefits and should be used whenever possible. Due to wide applications, higher efficiency, improved performance and low cost, PTC has become one of the useful components for enhancement of the solar energy applications.

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