A Review of Solar Thermal Systems Utilization for Industrial Process Heat Applications

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***Abstract* – This paper presents a literature review on Solar thermal systems for commercial and industrial application. The growth of solar thermal system for industrial use is slow as compare to that of residential application due to the higher level of temperature required for industrial process and the systems low efficiency. A number of research works on the development of solar thermal systems is discussed. The aim of this review is to identify the research trend of solar thermal systems for industrial applications. The review indicates that, there is a significant research development on the solar thermal but mainly focus on electricity generation but not for low and medium temperature industrial heat processes. The identified this research gap and recommends that, future research must focus on the low and medium temperature industrial applications**

Index Terms-**Solar thermal, industrial process heat, collector analysis.**

I. INTRODUCTION

THE solar energy uses a mere 8 minutes and 20 seconds to reach the earth after leaving the sun. The effective blackbody temperature of the sun is 5762k [1], however, the temperature in the central region is estimated at 8 x 106 to 40 x 106k. The total energy output of the sun is 3.8 x 1020MW which implies 63MW per square metre of the sun's surface area. The earth intercepts only small fraction of the total radiation [1]. It is estimated that the solar radiation following the planet is equal to the world energy demand for one year. How can this amount of solar energy be harness in order to determinate the utilization of non-environmental friendly energy sources? Several researches are done on the subject area and the numerous are on going to answer this question.

The idea of harnessing the sun's power with solar energy collectors was developed as far back as 212 BC when the Greek Scientist/Physician Archimedes devised a method to burn the Roman fleet. The Roman fleet was set ablaze by means of concave metallic mirror in the form hundreds of polished shields, all reflected on the same ship [2].

Athanasius Kircher (1601–1680) conducted some experiments to set fire to a woodpile at a distance in order to investigate the scientific validity of the Archimedes story [3]. In 18th century, polished-iron, glass lenses and mirrors were used to construct solar furnaces with capability of melting iron, copper and other metals. A French Scientist Antoine Lavoisier designed a furnace used a 1.32 metres lens in addition to a secondary lens of 0.2 metre to attain a high temperature of 1750 ^{o}C which turned to be the maximum achieved by man for one hundred years. During 19th century, solar energy was utilized to generate low-pressure steam to operate steam engines. Between the year 1864 and 1878, August Mouchot [3] constructed and operated several solar-powered steam engines. The initial designs of these solar-steam engines were not economically feasible until the year 1875, when Mouchot made a significant advance in the design of the solar collector by designing one in the form of truncated cone reflector. It consists of silver-plated metal plates with a collecting area of 18.6 m^2. Abel Pifre also designed solar engine having the same characteristic of Mouchot. However, the solar collectors were parabolic reflectors made of very small mirrors. [3,4]

In 1901, a 10m diameter focusing collector used to generate steam to power a water pumping system at a California Farm was installed by A.G. Eneas. The system consists of a large umbrella-like structure which received the full effect of sun's rays on the 1788 mirrors lined inside the surface. The boiler was located at a focal point where the sun's rays were concentrated. [1,3]

In 1904, a large solar furnace was constructed by a Portuguese Priest, Father Himalaya [3]. The system appeared to have an advance features. It was large off-axis, and haven a parabolic horn collector.

In 1912, Shuman and C.V. Boys developed the largest pumping plant in Meadi, Egypt. The system used long parabolic cylinders to focus sunlight into a long absorbing tube. During last 50 years many different solar thermal system are designed and constructed based on focusing collectors as a means of heating the working fluid which powered mechanical equipment.

Solar thermal system is fast developing for past two decades. Research has shown that, about 90% of the solar thermal systems developments are for residential applications. Its industrial utilization is less growing due to the economic dynamics of its utilization for industrial process. The reliability of solar thermal system for industrial process is a dependant of the following; temperature level of the process heat, climate condition, system integration and design method. The aim of this review is to identify the trend of research development on solar thermal systems for industrial applications.

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II. PROCESS TEMPERATURE RANGES

Beyond the residential application of solar thermal energy, there are numerous potential fields of application at a medium and medium – high temperature level. Heat production for industrial processes is the most essential of them (Table 1) [5]. Research indicates that about 15% of the total energy requirement in the southern European countries comes from industrial head demand. A number of investigations have shown that, several industrial sectors have been identified with potential utilization of solar energy. Typical industrial processes, which utilise heat at a mean temperature level are; sterillising, pasteurizing, hydrolyzing, drying, distillation and evaporation, polymerization, washing and cleaning. Industrial processes vary greatly in their required processing temperatures [5]. Figure 1 shows the percentage of process within the particular temperature ranges used by major industrial sectors.

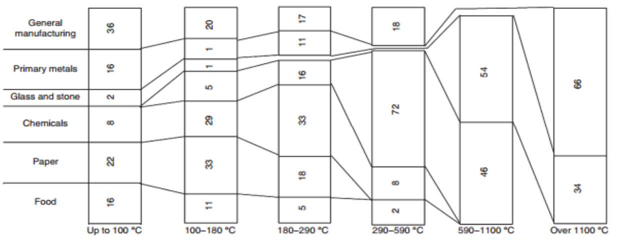

Figure 1 percentage of process temperature ranges in industrial sectors [5]

Table 1
Low- to medium-temperature solar industrial processes [5]

Sector	***Process***	***Required temperature range (°C)***
Food and beverages	Drying	30 - 90
	Washing	40 - 80
	Pasteurizing	80 - 110
	Boiling	95 - 105
	Sterilizing	140 - 150
	Heat treatment	40 - 60
	Preheating of feedwater to boilers	30 - 80
	Space heating of factories	30 -100
Textiles	Washing	40 - 80
	Bleaching	60 -100
	Dyeing	100 -160
	Preheating of feedwater to boilers	30 - 80
	Space heating of factories	30 -100
Chemicals	Boiling	95 - 105
	Distiling	110 -300
	Ancillary Processes	120 - 180
	Preheating of feedwater to boilers	30 - 80
	Space heating of factories	30 - 100

III. STATE OF THE ART INDUSTRIAL SOLAR THERMAL SYSTEM

A. Solar thermal system technologies

Optical concentration technologies are very essential when it comes to solar thermal system for providing thermal energy storage for industrial utilization. The following are the four popular concentrating solar thermal systems; parabolic trough collectors (PTC), linear Fresnel reflector systems (LF); central receiver systems (CRS) and Dish systems (DS)

B. Parabolic trough solar thermal system

Parabolic trough solar thermal system (PTSTS) consists of large fields of parabolic trough collectors and receivers, a heat transfer fluid, thermal energy storage (TES). The field consists of large modular arrays of single-axis-tracking solar collectors arranged in parallel rows. Each collector has a reflector with linear parabolic shape that directs the incident solar radiation out a linear receiver located at the focal line of the parabola. The sun is tracked from east to west during day by the collectors and the heat transfer fluid is heated within the receiver tubes to a temperature of about 390C. The heated HTF then flows through a heat exchanger, heat up the molten salt in the TES. In the case of electricity generation application, the heat exchanger generates steam which is fed to a conventional steam turbine generator for electricity production. The first solar electric generating systems was installed in southern California by LUZ international Inc. in 1984, these systems used single-axis parabolic trough collectors which tracks the sun with a north-south axis of rotation. [6]. The concentration factor between 19’1 and 26’1 were used and that reduces irradiative looses to a few percentage, but this concentration factor also limits the collection of diffuses radiation to very insignificant levels. The collectors used black chrome selective coatings which were improved by using metal ceramic coatings which improved the collector efficiency [7].

A schematic diagram of a PTC plant with a gas-fired backup boiler and TES similar to the Solana Generation Station in Arizona, currently considered to be the world’s largest parabolic trough power plant that has a 280 MW total capacity and 6 hours of thermal storage utilizing molten salt (Figure 3)

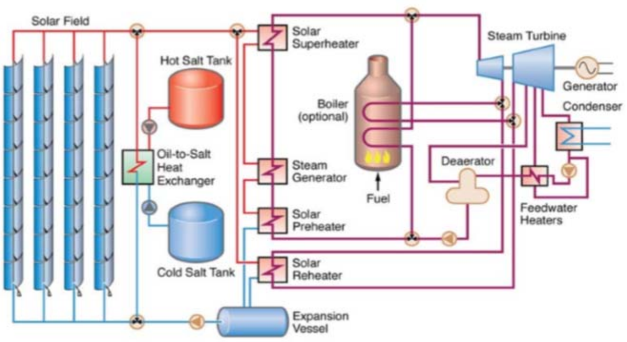

Fig. 2 *Parabolic trough plant with indirect two-tank thermal storage and fossil-fuel backup system*
Source: EPRI 2010 [8]

Fig. 3 Solana Generating Station in Gila Bend, Arizona, which is currently the world’s largest parabolic trough plant [8]

C. Linear Fresnel reflector

The technology of linear Fresnel Reflector relies on an array of linear mirror strips that concentrate light on to a fixed receiver mounted on a linear tower. The linear Fresnel reflector field can be imagined as a broken-up parabolic trough reflector, but unlike parabolic troughs where parabolic shape is always considered. Large stationary absorbers can be constructed. A representation of an element of an LFR collector field is shown in Fig. 4. The greatest advantage of LFR is that it uses flat or elastically curved reflectors that are cheaper as compared to parabolic glass reflectors. Additionally, these reflectors are mounted close to the ground, in turn minimizes structural requirements. This principle was first applied by the great solar pioneer Giorgio Francia [ ] who developed both linear and two-axis tracking Fresnel reflector systems at Genoa, Italy, in the 60s. These systems proved that the elevated temperatures could be reached using such systems but he proceeded to two-axis tracking, possibly because advanced selective coatings and secondary optics were not available [9].

In 1961, Francia built the first LFR, since then little was done until the last few years when two LFR designs (CLFR and polar munda) were developed in Australia and Belgium [8].

Between 1985 and 1990, LUZ International Limited Company designed and implemented eight commercial solar thermal power plants with PTC's. The plants are called SEGS and they are all located in the Mojave desert, California.

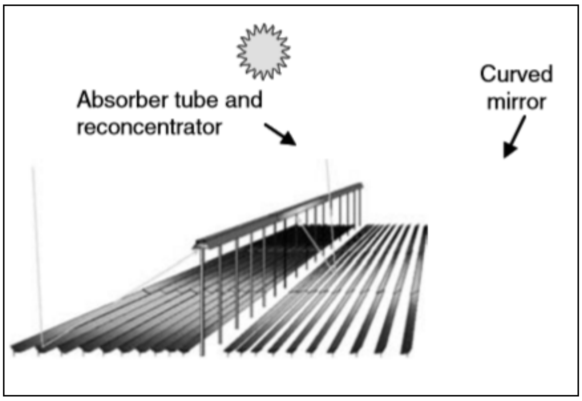

Fig. 4 Linear Fresnel Collector

D. Central Receiver Systems (CRSs)

For extremely high inputs of radiant energy, multiple flat mirrors, or heliostats with altazimuth mounts can be employed to reflect their incident direct solar radiation onto a common target.

This is called the heliostat field or central receiver collector. By using slightly concave mirror segments on the heliostats, large amounts of thermal energy can be directed into the cavity of a steam generator to produce steam at high temperature and pressure. The concentrated heat energy absorbed by the receiver is transferred to a circulating fluid that can be stored and later used to produce power.

Fig. 5 LH-2.2 heliostats at Ivanpah

The advantages of HFC are:

- HFC collect solar energy optically and transfer it to a single receiver, thus reduces thermal-energy transport requirements.
- High concentration ratios (300– 1500) in achieved.
- HFC can conveniently store thermal energy.
- They are quite large (generally more than 10 MW) and thus benefit from economies of scale.

Few of the large number of STPP tower projects have been tested all over the world (Table 2). These were demonstration systems between 0-5 and 10MWand most of them were operated in the 80's [10,11]

Table 2
Experimental power towers in the world [12]

Project	Country	Power (MW_e)	Heat Transfer Fluid	Storage Media	Beginning Operation
SSPS	Spain	0.5	Liquid sodium	Sodium	1981
Eurelios	Italy	1	Steam	Nitrate salt/water	1981
Sunshine	Japan	1	Steam	Nitrate salt/water	1981
Solar One	U.S.A.	10	Steam	Oil/rock	1982
CESA-1	Spain	1	Steam	Nitrate salt	1982
MSEE/Cat B	U.S.A.	1	Nitrate salt	Nitrate salt	1983
Themis	France	2.5	Hitec salt	Hitech salt	1984
SPP-5	Russia	5	Steam	Water/steam	1986
TSA	Spain	1	Air	Ceramic	1993
Solar two	U.S.A.	10	Nitrate salt	Nitrate salt	1996
ConSolar	Israel	0.5^a	Pressurized air	Fossil hybrid	2001
SOLGATE	Spain	0.3	Pressurized air	Fossil hybrid	2002
PS10	Spain	11	Water/steam	Saturated steam	2006
$PS20^b$	Spain	20	Water/steam	Saturated steam	2008
Solar Tres^b	Spain	17	Nitrate salt	Nitrate salt	2009

E. Parabolic Dish Reflector

A parabolic dish reflector is a point-focus collector which tracks the sun in two axes, directing solar energy onto a receiver positioned at the focal point of the dish. The dish structure usually tracks the sun to reflect the beam into the thermal receiver. The radiant solar energy is absorbed by the receiver, converting it into thermal energy in a circulating fluid. The heat energy can then either be converted into electricity using an engine-generator coupled directly to the receiver, or it can be transported through pipes to a central power-conversion system. Parabolic-dish systems can achieve temperatures in excess of 1500 ºC.

Parabolic dishes have the following advantages:

- PDRs are the most efficient of all collectors systems due to the sun tracking.
- PDRs typically have concentration ratio in the range of 600–2000, hence higher efficiency

- They have modular collector and receiver units that can either function independently or as part of a larger system of dishes.

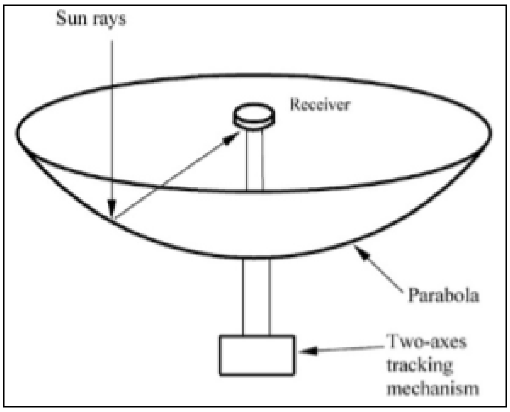

Fig. 6 Parabolic dish collector

Typical application of PDC is Dish/Stirling Development of dish/stirling started in the early 1980's. A facet-type concentrator with second-surface mirrors was the first generation of dishes with concentration records (C = 3000). A prototype of 25 kW vanguard-1 was built by Advance and operated at Rancho Mirage, started in the early 1980's. A facet-type concentrator with second-surface mirrors was the first generation of dishes with concentration records (C = 3000). A prototype of 25 kW vanguard-1 was built by Advance and operated at Rancho Mirage, California. The results of 18 month operation were published by EPRI [13]. An improved dish system has developed by McDonnell Douglas utilizing the same technology and the same engine. Further research seek to reduced the system costs developed lighter and less expensive reflectors made of polymers or thin glass glued into resin-based structures. Typical concentration was in the range of 600-1000 and working temperature of about 650 ^{o}C.

IV. CURRENT RESEARCH DEVELOPMENTS

There has been a tremendous achievement on solar thermal research for past two decades. This section presents some of the current research conduction for past ten years. Most of the researches focus on electricity generation. It has been reported in the Solar PACES [ ] that CSP plants of total capacity of 4429 MW were operational across the world and about 5684 MW capacity are under construction or development by the end of the year 2014. The following solar thermal power generation technologies have attained a maturity level of commercialization; parabolic trough collector (PTC), central receiver system (CRS) and linear Fresnel reflector (LFR). However, the costs of the solar field accounts for 40-50% of the total project cost. [P. Viebahn and IEA] The cost can be reduced by improving the systems efficiency which directly depends on some design parameters.

Chandam Sharma, et.al. [14] presented a study on the effect of design parameters on the performance of linear solar concentrator based thermal power plants in India. The three design parameters thus DNI, Solar multiple and hours of thermal storage were analysed with System Advisor Model for eight locations in India. The annual electricity output was estimated using radiation data of SEC-NREL. Levelized unit cost of electricity (LUCE) was estimated benchmark capital cost and other financial conditions. The results of the study shown that for design DNI of 950 W/m^2, LUCE was minimized in solar multiple range of 1.4 – 1.6 for PTC based plants and of 1.8 – 2.0 for LFR based plants. With a solar multiple of 1.0, LUCE was minimum in design DNI range of 550 – 700 W/m^2 for PTC based plants and 450-550 W/m^2 for LFR based plants.

Xiaoche Lu et. al. [15], presented a research article on utilization of solar thermal system that supplies thermal and electrical energy for the scientific equipments and human beings for lunar outposts. The objective of the study was to analyse the performance of a lunar based solar thermal power system with rigorith thermal storage. The performance analysis was conducted by the finite time thermodynamics to consider the major irreversible losses. The study analysed some key design parameters for optimization. The model simulation revealed that, lunar based solar thermal power system with rigorith thermal storage can meet the requirement of the continuous energy supply for the lunar out posts.

Abdulrahman et. al. [16], proposed a methodology to define a framework for concentrated solar power assessment for the purpose of planning of solar thermal energy projects. The study obtained a generic value tree of evaluation parameters for solar thermal power technologies in developing countries Delphi method was used to conduct expert elicitation.

Performance of a thermal collector can be evaluated by determination of thermal efficiency in steady state test of solar simulators. Hasan Sabahi, et. al. [17], presented a novel design of a solar simulator for investigating the performance of solar collectors for scientific and industrial purposes. The design employed metal halid as a source of irradiance. The light field was checked for uniformity of the irradiated surface by simulating the light field with DIALux. The intensity of the irradiance received by their radiated surface vary from 100 W/m^2 to 1000 W/m^2, is controlled by changing the distance of testing surface from lamps.

Solar thermal with CCPP Application

Solar Combined Cycle Power Plant is a combination of concentrated Solar Power (CSP) and Natural Gas-fired Combined Cycle Power Plant. This hybridization was a potential of reducing the costs of solar energy for electricity generation. The concept of hybridizing CSP and gas power plant was first proposed by Luz Solar International in the early 1990's. The Archimed project in sicily. Italy was the first successful plant with this concept. The plant consists of two 380 MW gas powered combined cycle and 5WM parabolic trough solar field. [18]. As of 2015 number of solar combined cycle power plants are recorded in Florida, Morocco, Egypt and Iran [19-22]. The evaluation of the technical and economic advantages had been a research focus since the adoption of this hybrid concept. (ISCC).

Peterseim et. al. [22] assessed all suitable CSP's technologies for integration with Rankine cycle power plants. The investigation concluded that Fresnel and parabolic trough which are line focusing system are the best for integration of lower temperature steam (<400C). The investigation also concluded that Fresnel systems are considered to be the most efficient for medium temperature

(380C – 450C) and the direct steam generation solar towers are the best for higher temperatures (>450C).

Kelly et. al. [23] conducted a study on double integrated plant designs using Gate cycle modelling software and the conclusion was that; annual solar contributions of up to 12% in an ISCC offer economic advantages over conventional solar – only parabolic trough power plants. The study also concluded that, the production of high-pressure saturated steam is the most efficient utilization of solar thermal energy.

Rovira et. al [24], conducted research on a number of ISCC configurations with solar parabolic trough collectors and the results shown that, the direct steam generation (DSG) configuration is considered to be the best choice for solar energy integration. Li and Yang, [25] conducted a research on a new ISCC system with a two-stage solar DSG input to increase the solar share. Comparison analysis shown that, the two-stage ISCC presented better performance and up to 30% increased net solar-to-electricity efficiency.

Bandar Jubran Alqahtani et. al. [26] studied the economic and environmental benefits of an ISCC power plant relative to a stand-alone CSP with energy storage and a natural gas-fired combined cycle plant. The study results show that integrating the CSP into an ISCC reduces the levelized cost of energy of solar generated electricity by 35-40% relative to a stand-alone CSP Plant.

V. FINAL REMARKS

Even though the review unable to cover wide area of the solar thermal system, the few discovered research reports on integrated solar thermal system revealed that, there is a significant research work on the solar thermal since past two decades. Much of the work focuses on the system efficiency improvement whiles little on system suitability for process heating. Almost all the reports reviewed focused on system integration for power generation. High temperature <400C is required to generate steam for electricity generation, however, process heat for the following process; sterilization, pasteurization, drying, washing and cleaning required temperature level ranging from low to medium (50ºC – 300ºC). The low/medium temperature heat demand for the above industrial process is much higher in an industrialized country than the higher temperature for electricity generation. Therefore this paper recommends that future research must focus on the integration of solar thermal for low and medium heat applications.

VI. CONCLUSION

This review has been focused on the recent research development in the field of solar thermal for industrial utilization. The review has shown that most of the researches on industrial solar thermal systems are focused on electricity generation. Less attention is given to the area of low and medium temperature heat process applications. This is a clear research gap and therefore the paper recommends that, future research must focus on the solar thermal systems for low and medium temperature process heat applications.

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