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Advances in Solar Thermal Energy : A Review

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ABSTRACT

Solar thermal collectors are a promising technology for reducing reliance on fossil fuels in the industrial sector, thus mitigating the consequences of climate change. This review paper comprehensively evaluates contemporary literature on solar thermal collectors by highlighting their eco-friendliness, energy security benefits, and potential as an alternative to fossil fuels in process heating applications. The article examines the challenges and limitations that impede the global acceptance of solar thermal systems (STSs) in the industrial sector. It also discusses the potential contribution of STSs in achieving sustainable development goals. Furthermore, new engineering applications of STSs are explored, with a focus on design, optimization, materials, and integration with interdisciplinary science and technologies.

Keywords : Solar Thermal Energy, Solar Collectors, Heat Storage, Applications, Renewable Energy

I. INTRODUCTION

On a global scale, the expansion, upgradation, and financial improvement of nations in the industrial sector critically depend on energy as a fundamental necessity. The energy system has undergone substantial transformations since the era of industrialization. With rising wealth and demographics, there is a growing demand for energy across many countries globally. Without improvements in energy efficiency, this escalating demand will lead to a continual increase in global energy consumption, as depicted in Table 1 [1], which illustrates the consumption of various resources worldwide in 2022. Global energy demand is still increasing, although at a somewhat slower rate of about 1% to 2% annually.

A. Importance of solar thermal energy as renewable energy: Solar thermal energy is important in the context of renewable energy as it provides a feasible approach to decrease dependency on fossil fuels, especially in the industrial sector. Solar thermal collectors (SHC) are recognized for harnessing solar energy especially for process heating, providing ecological benefits, energy safety, and a promising replacement of fossil fuels [2].

Energy Consumption Globally	2022 (TWh)	In percentage
Traditional Biomass	11111	6.21

Fable I : Global energy	⁷ consumption	in the year 2022
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Coal	44854	25.09
Oil	52870	29.57
Natural Gas	39413	22.04
Nuclear Power	6702	3.75
Hydropower	11300	6.32
Wind power	5488	3.07
Solar power	3448	1.93
Biofuels	1199	0.67
Other renewables	2414	1.35

Solar thermal systems provide a more cost-effective solution for process heating than photovoltaic (PV) systems, the use of renewable energy sources can make them a practical substitute for process heating that is based on fossil fuels. The intermittent nature of sunlight is addressed through the use of solar thermal energy storage systems, ensuring a reliable energy supply for industrial processes [3].

Incorporating solar thermal energy in industrial sector globally, can help reduce the usage of fossil fuels and mitigate climate change. Solar thermal energy complements different sources of renewable energy, like solar photovoltaic cell, wind power etc., in achieving a sustainable and diversified energy mix [2].

B. Motivation for exploring diverse applications and methods: The world is moving towards sustainable production and consumption systems, which has resulted in a greater use of renewable energy sources, such as solar power. Technologies like concentrated solar power (CSP) are considered to be one of the capable ways of producing electricity in the future. The intermittent nature of solar energy poses a challenge for its integration into the energy grid. Efficient and affordable thermal energy storage (TES) systems are being explored for CSP applications. These systems offer a reliable and eco-friendly alternative to traditional energy storage methods, making them crucial for the future of clean energy. The development of diverse applications and methods of solar power generation and enable its integration into the energy grid [4]. It is imperative to explore diverse applications and methods for thermal energy from the sun to minimize the usage of fossil fuels and mitigate the consequences of climate change. The industrial sector mostly relies on traditional fossil fuels for heat energy, and exploring diverse applications and methods of solar thermal energy is able to generate a strategy that reduces this dependence practically. Solar thermal collectors offer numerous environmental benefits, enhance energy security and have potential as a replacement for fossil fuels, making them a promising technology for various industrial processes [2].

This review paper focuses on identifying the global progress of acquiring solar thermal energy by developing solar collectors, it is also investigated the specific heat and temperature requirements for several industries. It explores the integration of solar systems for industrial process heating and identifies common thermal applications used in industrial processes. The paper discusses the use of thermal energy of sun for industrial



process heating, and examines various studies on the subject. It also discussed the different solar thermal energy extraction technologies and their key characteristics and their application arears.

Thermal Energy requirements for Industrial Processes

Large scale investigation has shown that solar thermal process heating is practical and can reduce $[CO]_2$ emissions and external costs. Solar thermal systems have potential in various industrial sectors in different countries, such as China and Switzerland, to reduce $[CO]_2$ emissions and meet process heating demands. Including solar industrial process heat in German enterprises can fulfil a significant part of the heating demand and reduce greenhouse gas (GHG) emissions. Addition of parabolic thermal energy collectors in industry for the application of heat in process has the potential to reduce the cost of heat and GHG emissions. Technologies of collecting Solar thermal energy can play a vital role in heating process at industries, globally [5–7].

Solar thermal energy is produced by converting sunlight into heat. To collect solar radiation, a device called a solar collector is used, as shown in Figure 1. The heat generated by this process can be used for a variety of industrial applications or stored for future use, such as heating water or air for residential or commercial purposes. Process heating systems typically include a heating unit that produces heat and a circulation system that transfers thermal energy to its intended application.



Fig.1 Schematics diagram of working principal of a typical Solar thermal collector

Solar thermal technology has been extensively studied for its feasibility and characteristics. Flat-plate collectors are cost-effective for temperatures under 60°C, whereas evacuated tube collectors (ETC) are more feasible for temperatures greater than 70°C. Researchers from various countries conducted systematic reviews to recommend suitable solar heating systems for different industries. Different collector systems, such as flat plate and concentrating collectors, have been evaluated for their reliability and effectiveness in various climatic conditions for industrial process heat systems. Additionally, a combination of photovoltaic (PV) cells and solar thermal collector systems can minimize fossil fuel use in process heating [8–10].

Solar Thermal Energy and Collectors

Over the past decade, significant progress has been made in solar energy (SE) technologies, offering a range of options with varying costs. The increasing global demand for energy, driven by economic progress, in addition with escalating costs of fossil fuels, presents a critical challenge. Conventional energy sources have limited reserves, necessitating a shift towards sustainable alternatives. Sunlight, as Earth's most abundant energy source,

181

can be harnessed through various means such as solar thermal energy and photovoltaic cells. While PV cells efficiently convert solar energy into electricity, they are not without limitations, converting only about 15-20% of solar radiation into electrical energy [11].

In contrast, solar thermal collectors are devices that convert solar energy directly into heat, offering a more efficient solution for certain applications. Emerging technologies like solar concentrated photovoltaic thermal (CPVT) and photovoltaic thermal (PVT) systems integrate electrical and thermal outputs, showing promise for increased efficiency. However, these integrated systems are currently limited to research and require further assessment for real-world feasibility before widespread adoption. The market offers a variety of solar thermal collectors, each with its unique characteristics and developmental trajectories. This study offers an overview of the different types of collectors (as shown in Fig. 2) used in solar thermal energy systems worldwide. The paper discusses the latest advancements and challenges in this field [12, 13].



Fig.2 Classification of solar thermal collectors [9, 14]

As indicated from the Fig. 2 solar thermal collectors can be broadly classified in two groups (a) non-concentrating and (b) concentrating solar thermal collectors.

Flat plate collector is a typical example of non-concentration thermal collector as shown in Fig. 3. Thermal energy absorber plats are placed such a manner that solar radiation heats the plates directly and the absorbed heat is transferred through fluid flowing through the copper tubes placed beneath the heat absorber plate.





On the counterpart, in concentrating solar thermal collectors' solar energy is concentrated towards the absorbent and then that is collected and transferred to the intended places. Parabolic Reflector is an example the concentrating type of solar thermal collector and it's working procedure is shown through a schematic diagram Fig. 4. Here, sun lights are reflected and concentrated through a parabolic reflector. A receiver is placed on the concentrating point to absorb the heat energy and subsequently transfer to the intended places.



Use of Solar Thermal Energy in Industries

Solar thermal energy holds potential for various applications from medium to high temperatures (80–240°C), besides its use at lower temperatures. This is an excellent source of direct heat for industrial processes, and a reliable power generator for electricity. Present study focuses solely on the thermal aspects of solar energy systems. A schematic diagram in Fig. 5 illustrates a solar collector system combined with auxiliary sources to supply process heat for various industries with different process needs. However, implementing solar power for industrial use poses several challenges, which will be discussed later in this paper.



Fig. 4: A Schematic diagram of Concentrating type of Solar Collector (Parabolic Reflector)



Fig. 5 Integration of solar heat/thermal energy to industrial processes

Many industrial processes use various types of solar thermal collectors to harness the heat energy from the sun [15, 16].

Some potential application areas of heat are as follows:



- (a) Food Industry
- (b) Automobile Industry
- (c) Paper Industry
- (d) Textile Industry
- (e) Pharmaceuticals
- (f) Chemical Products
- (g) Agricultural Industry
- (h) Mining Industry
- (i) Solar Energy

Advantages and Limitations of Solar Thermal Collectors

After analyzing the discussions above, it is clear that solar thermal collectors offer multiple environmental advantages, energy security, and have the potential to replace fossil fuels in industrial process heating applications. Solar energy systems that utilize various collectors have a wide range of applications including space heating and cooling, water desalination, and industrial processes. However, there are specific limitations such as efficiency losses due to dust accumulation, high initial costs, and intermittency of solar radiation for some types of collectors. Additionally, there are significant challenges related to storing the energy produced by solar thermal collectors, as well as the high initial costs associated with them. The Solar Thermal Energy Storage (STES) system faces several challenges and limitations that hinder its widespread adoption as a fossil fuel alternative. Here are some of the major challenges storing the energy:

(a) PCM Leakage: Phase-change materials (PCM) are effective for storing solar heat energy, but there is a risk of leakage once the PCM melts, leading to fluid flow.

(b) Heat Loss: Increased temperature differences between the STES system and surrounding temperatures lead to higher heat losses. Inadequate insulation also contributes to additional heat loss.

(c) Pressure: Water, commonly used in STES systems, has a high vapor pressure, requiring thick containers that increase costs and may lead to leakage issues.

(d) Supercooling: Significant temperature variations during charging and discharging cycles can cause supercooling, particularly with PCM-type thermal storage materials.

(e) Corrosion: In thermal energy storage systems, the use of inorganic materials can lead to severe vessel corrosion over time.

(f) Safety Concerns: Many materials used in these systems pose safety risks, such as in flammability. Organic oils, in particular, can be challenging to handle safely.

Addressing these challenges is crucial for enhancing the efficiency, reliability, and safety of STES systems, results solar thermal energy sources are becoming more feasible options compared to traditional fossil fuelbased energy sources.

Conclusion

The selection of solar thermal technology in industrial processes is primarily driven by temperature requirements. Different solar thermal collectors are distinguished based on their ability to deliver specific temperature ranges. For instance, solar collectors like Compound Parabolic Collectors (CPC), Flat Plate Collectors (FPC), or Evacuated Tube Collectors (ETC), can provide temperatures ranging from 60 to 240°C, 30 to 80°C, and 50 to 200°C, respectively. In cases where existing collectors fall short, cascading or stacking



multiple collectors can be a viable solution to reach higher temperatures. Apart from temperature considerations, other factors such as land availability, temperature load fluctuations, scheduling flexibility, thermal storage capabilities, and integration options play crucial roles in selecting the appropriate solar thermal technology.

Based on this research, the following conclusions are drawn:

The industrial sector's significant energy consumption and greenhouse gas emissions from fossil fuel usage highlight the urgent need for sustainable alternatives. Solar thermal collectors offer a viable solution by harnessing solar energy, contributing to reduced carbon emissions and long-term sustainability.

Solar thermal collectors find diverse applications including space heating and cooling, refrigeration, CCS technology, water desalination, and industrial process heating. Combined systems that utilize both water and air as working fluids exhibit greater efficiency in comparison to individual systems.

Solar thermal energy has the ability to meet the heating demands of various industries, its intermittent nature necessitates the use of energy storage systems to ensure continuous operation.

This study offers key insights for decision-makers to integrate solar thermal energy into industrial processes and promote sustainable development.

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