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A review of latest developments, progress, and applications of heat pipe solar collectors

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ABSTRACT

Among all the available solutions to the current high energy demand and consequent economic and environmental problems, solar energy, without any doubt, is one of the most promising and widespread solutions. However, conventional solar systems face some intractable challenges affecting their technical performance and economic feasibility. To overcome these challenges, increasing attention has been drawn towards the utilization of heat pipes, as an efficient heat transfer technology, in conventional solar systems. To the authors' knowledge, despite many valuable studies on heat pipe solar collectors (mainly during the last decade), a comprehensive review which surveys and summarizes those studies and identifies the research gaps in this field has not been published to date. This review paper provides an overview of the recent studies on heat pipe solar collectors (HPSCs), their utilization in different domestic, industrial, and innovative applications, challenges, and future research potentials. The concept and principles of HPSCs are first introduced and a review of the previous studies to improve both energy efficiency and cost effectiveness of these collectors is presented. Moreover, a concise section is dedicated to mathematical modeling to demonstrate suitable methods for simulating the performance of HPSCs. Also, the latest applications of HPSCs in water heating, desalination, space heating, and electricity generation systems are reviewed, and finally, some recommendations for future research directions, regarding both development and new applications, are made.

1. Introduction

Availability, renewability, great potential, and being environment friendly has turned solar energy into the best possible renewable option to meet increasing energy demand. However, intractable challenges in regard to efficient collection and effective storage of this free and clean energy create serious limitations to its industrial applications. Solar energy is accessible only during daytime so it has to be absorbed, transferred, and stored efficiently. That is why solar collectors are the most important component of all solar-driven systems [1].

Fundamentally, there are three types of solar collectors: Flat Plate Solar Collectors (FPSCs), Evacuated Tube Solar Collectors (ETSCs), and Heat Pipe Solar Collectors (HPSCs). FPSCs are designed and used in a wide range of forms. Although FPSCs are durable, cheap, and manufactured easily, their application is technically and economically feasible only in sunny warm climates and/or during the summer. For instance, in cold climatic conditions, cloudy days, and windy areas, their efficiency reaches 75% in summer but drops to less than 40% when solar radiation intensity and ambient temperature are not high [2]. FPSCs are also vulnerable to moisture which affects their durability and decreases the overall efficiency of the solar energy system in which they are used [3].

Another significant drawback of FPSCs is their unsuitability for applications with high operating temperatures due to increased thermal losses and, hence, significantly decreased efficiency of the collector and the overall solar energy system. Selecting better absorbing surfaces and applying anti-reflective glass and extra insulation have been proposed to rectify these issues; however, the associated extra costs affect the economic feasibility of these systems [4]. At the same time, flat plate collectors have high hydraulic resistances [5] and should be utilized with sun trackers for a better performance which also increases their operational and maintenance costs [6].

ETSCs were introduced to address the challenges confronted by FPSCs, especially to improve their efficiency at high temperatures. In this type of collector, the space between the two layers of glass tubes is vacuumed and selective absorbers and transmitters are applied to decrease thermal losses [7]. This has significantly improved the performance of ETSCs even in cold environments with low solar radiation [8,9]. Another key advantage of these collectors is their low maintenance cost [10]. These led to an increase in ETSCs' market share in

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China from 88% in 2003 [11] to 95% in 2009 [12].

Despite these proven advantages of ETSCs, the possibility of overheating remains as one of the most important drawbacks of ETSCs. For instance, while the temperature limit for domestic applications is 100 °C, these collectors can easily cross this limit. Therefore, enough working fluid should continuously be available to receive the extra thermal energy; otherwise material problems or vacuum loss occurs [2]. Another drawback of these collectors is their high initial costs [13]. Also, ETSCs should be handled with care as they are made from a special type of glass and are fragile [2].

Heat pipe solar collectors (HPSCs) which have the advantages of both evacuated tube collectors and heat pipes were introduced to overcome the limitations of FPSCs and ETSCs. HPSCs remove heat from the absorbing surface with the highest efficiency and transfer it to the working fluid with the lowest thermal and hydraulic resistances [14]. In this type of solar collector, heat pipes function by applying the latent heat instead of sensible heat and heat transfer only occurs by phase change process of the working fluid which significantly reduces temperature drop, increases heat transfer capability, and decreases the required heat transfer area and weight [11]. Also, the very high heat transfer coefficient of phase change process has turned HPSCs into highly efficient heat transfer devices [15]. Furthermore, the completely natural movement of working fluid eliminates the necessity of mechanical devices such as pumps [11]. Additionally, HPSCs control operating temperature and prevent overheating, which is a common problem in solar applications [16,17]. Also, while the elimination of corrosion and freezing increase the operating life of HPSCs [18], they can simply be fitted in roofs or facade side of buildings due to their light weight and simple design [19].

Unique features and advantages of HPSCs have turned them into an attractive option for solar applications and drawn significant attention in recent years. To the authors' knowledge, there is no review paper available to date on HPSCs, their applications in different solar energy systems, and investigations to improve their field performance. Therefore, this paper reviews the most significant studies on: (i) heat pipe solar collectors, their types and progress; (ii) performance of HPSCs in different domestic and industrial solar systems; and (iii) innovative applications, challenges, and the future research potentials in this field. This information will be a valuable reference for those who are interested in or intend to perform research in the field of solar thermal engineering, in particular in the field of heat pipe solar collectors.

2. Structure, performance and advancements of heat pipe solar collectors (HPSCs)

This section presents details about structure of HPSCs (i.e. heat pipes and glass evacuated tubes) along with the latest studies to analyze and improve the performance of these collectors and recent advancements in this field.

2.1. Structure of HPSCs

2.1.1. Heat pipe

HPSCs include two major components: i) heat pipe, and ii) glass evacuated tube. A heat pipe is principally a sealed tube which holds a wick structure and a specific amount of fluid (e.g., water, methanol, and ethanol) inside it acting as the working fluid [10]. Fig. 1 shows the longitudinal and the cross sectional views of a typical heat pipe which demonstrate its working mechanisms including (i) evaporation, (ii) adiabatic transfer, and (iii) condensation.

Heat passes through the evaporator section and provides the required thermal energy for evaporation of working liquid. Then, the vapor moves towards the adiabatic section then the condenser section, where the vapor turns into liquid by losing its thermal energy. The liquid then returns to the evaporator section via the capillary wick structure and the cycle continues [21]. The working fluid, the wick structure, and the tube are the main components of all types of heat pipes. The selection of working fluid depends greatly on the fluid properties, the compatibility with the wick and tube materials, and the operating temperature range [22]. Among all the properties of the working fluids, thermal conductivity has a significant effect on improving the thermal performance of heat pipes. Some researchers focused on increasing thermal conductivity by adding nanofluids to the base working fluid [23,24]. A comprehensive review paper has been published summarizing the relevant studies in this field and also specifying the perspective of using nanofluids in heat pipes for further studies [25].

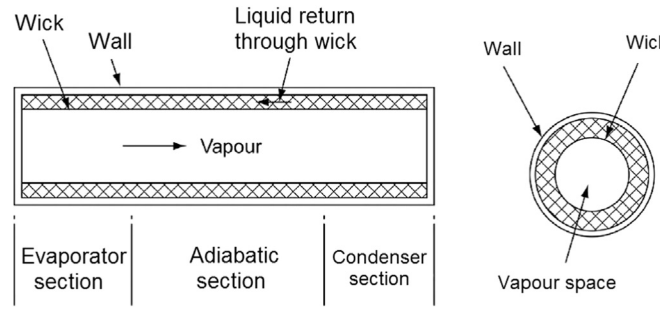

Fig. 1. Longitudinal section and cross sectional view of a typical heat pipe [20].

Since the main focus of this review is on the heat pipe solar collectors rather than the heat pipe itself, more details about the heat pipe structure, components, characteristics, modeling, design, various applications, and limitations can be found in the references presented in Table 1.

2.1.2. Evacuated tubes

Evacuated tubes are made of glass and once a number of them are placed in a parallel arrangement, they form the evacuated tube solar collector (ETSC). Each tube consists of one inner and one outer tube with a very small light reflection (Fig. 2). The inner tube acts as the absorbing surface, while the outer tube acts as the transparent glass to facilitate the passage of solar radiation. The space between the two concentric tubes is vacuumed to create thermal insulation [30].

In contrast to FPSCs, ETSCs do not require sun trackers due to their cylindrical absorbing surface. Furthermore, the effect of low solar radiation, low ambient temperature, and high wind velocity on the performance of ETSCs is considerably less. Also the vacuumed space between the glass pipes significantly decreases both heat losses and maintenance costs [32]. These unique features of evacuated tube collectors have attracted researcher attention.

Another type of ETSCs which combines U-shape copper tubes with the evacuated glass tubes is called U-type ETC. The U-tube ETC has a simple structure and is also tolerant to high pressure [33]. Fig. 3 illustrates the U-type ETC along with its cross section view.

One of the most important design parameters of ETSCs is the shape of the absorber. Fig. 4 shows different shapes of the absorbers used in ETSCs including tube welded inside a circular fin, finned tube, U tube welded on a copper plate, and U tube welded inside a rectangular duct. According to the theoretical and experimental investigations, U-tube welded inside a circular fin shows better performance in ideal conditions compared to other three shapes. However, if parameters such as the shadow due to the adjacent tubes and the effects of the diffuse irradiation are considered, U-tube welded on a copper plate has the best thermal performance [35].

Table 2 summarizes the most important and relevant studies involving ETSCs along with their description and key findings.

2.1.3. Assimilation of heat pipes and evacuated tubes

When the evacuated tubes and heat pipes are combined, they form