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Heat transfer enhancement in parabolic trough collectors: A comprehensive review

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A R T I C L E I N F O

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A B S T R A C T

Improving the performance of solar collectors has been recently a subject of intense research because of its advantages such as a decrease in the size and cost of systems and an increase in the thermal performance. Among solar collectors, parabolic trough collectors (PTCs) are of great importance because of their applicability. PTCs are widely used in Concentrated Solar Power Plants (CSP), and Industrial Process Heat (IPH), which demand high and low-temperature heat, respectively. Thermal oils have been extensively utilized as the working fluids in solar thermal electric plants (STE) with PTCs. However, their operating temperature limitation and environmental pollution have caused employing alternative working fluids. The present study is conducted to evaluate the thermal efficiency enhancement methods in PTCs. The effect of parameters such as absorber tube coating and design parameters on the performance of PTCs is also discussed. Moreover, passive methods for heat transfer enhancement in PTCs are investigated and the effect of using nanofluids as a working fluid is reviewed. This review can open new horizons for further investigations in this field.

1. Introduction

The use of conventional energy such as fossil fuels has led to environmental damage such as pollution, climate change, and acid rain. To overcome these problems, scientists have investigated alternative energy resources, which are environment-friendly and widely available. Among these energy categories, solar and wind energy are huge green energy sources [1]. Solar energy is an alternative energy, which is supplied by the sun. The sun is a 1.39×10^9 m diameter composed of a hot gaseous matter. Chemical reactions occur inside the sun, leading to energy production at temperatures of many millions. Only a small share of this energy reaches the Earth due to absorption and diffusion in the atmosphere. Therefore, solar systems can turn this kind of energy into other beneficial energies [2]. Among solar systems, parabolic trough collectors (PTCs) are of great importance because of their applicability (Fig. 1). PTCs are line-focus concentrators, which concentrate direct solar radiation on the axis of the collector. They consist of a receiver tube containing working fluid. The working fluid absorbs solar heat flux from the walls of the tube. PTCs are widely used in Concentrated Solar Power Plants (CSP), and Industrial Process Heat (IPH), which demand high and low-temperature heat, respectively. The working fluid temperature in CSPs with PTCs can exceed 500 °C, which is beneficial for steam power cycles. In IPH applications, the range of working fluid temperature is 100–250 °C, which can be used in supplying low-temperature requirements such as space heating and domestic hot water for public places [3]. Several parameters can affect PTCs performance. The investigation of the effect of these parameters on pressure drop, heat transfer, and the thermal efficiency of collectors is necessary. Moreover, the energy loss in PTCs includes optical loss, thermal loss, and cosine loss. The optical loss is mainly caused by the materials of the mirror and glass cover (GC). The temperature difference between the absorber tube and the ambient causes the thermal loss. In this regard, the non-zero-degree incidence angle leads to cosine loss [4]. These parameters should be considered in the design of PTCs to achieve the optimal structure.

As a result, the comprehensive review can improve our understanding of other researchers' works to optimize the design and structure of PTCs, decrease optical and thermal losses, and result in a fair classification.

Many research has been conducted in the field of PTCs performance improvements. In the present study, not only the heat transfer enhancement methods, but also design parameters (because of their importance in reducing energy loss in PTCs) are considered.

A review of the technical literature reveals numerous studies on the

Abbreviations: CFD, Computational Fluid Dynamics; CSP, Concentrated Solar Power Plants; EES, Engineering Equation Solver; erf (), error function; FVM, Finite Volume Method; GC, Glass Cover; IPH, Industrial Process Heat; MCRT, Monte Carlo ray-tracing (MCRT); PTC, Parabolic Trough Collector; TPTC, Transparent Parabolic Trough Collector

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Nomenclature

Symbols

A	Aperture width, (m)
A_a	Aperture area of the PTC, (m^2)
A_f	Geometric factor
a_{ij}	Projection surface element areas, (m^2) on the aperture plane
A_l	Total aperture area loss, (m^2)
A_{tot}	Total aperture area, (m^2)
D	Absorber tube diameter, (m)
Ex_a	Absorbed solar radiation exergy, (W)
Ex_u	receiver tube exergy rate transferred to heat transfer fluid, (W)
F	Focal length of the parabola, (m)
F	Friction factor
F	Cosine loss factor
H	The height of pin fin, (m)
Hp	Height of the parabola, (m)
I_D	direct normal irradiance (W/m^2)
K_θ	Incidence angle modifier
L	The length of absorber tube, (m)
M	mass flow rate, (kg/s)
Nu	Nusselt number, (dimensionless)
P	The distance between two consecutive corrugations, (m)
R	The absorber tube diameter, (m)
Re	Reynolds number, (dimensionless)
S	entropy (J/K)
sdx_{ij}	Local slope deviation
T	The thickness of pin fin, (m)
T	Temperature, (K)
W_a	Aperture of the parabola, (m)

Greek symbols

α	Receiver absorptance
B	Thermal expansion coefficient, (1/K)
η_{th}	Thermal efficiency
γ	Intercept factor
δ	The distance between two consecutive pin fins, (m)
η	Thermal performance
η_0	Optical efficiency
θ	Incidence angle, (°)
ρ	Mirror reflectance
τ	Glass cover transmittance
φ_r	Rim angle, (°)

Subscripts and superscripts

amb	Ambient
c	clean state of the mirror
d	dirty state of the mirror
ex	Exergetic
fm	mean fluid
G	Glass
i	in
o	out
P	Plain
r	receiver
S	Sun

changes in geometry [10–63], tracker [26–32], a coating of absorber tube [64–74], passive methods [75–101], and the types of working fluids [102–156]. Each of these methods is discussed in the following sections. This study aims to collect and review previous research in the field of thermal performance improvement of PTCs. Besides, the methods of heat transfer enhancement in PTCs system are reviewed. Finally, based on the previous research some suggestions are proposed for future works.

2. Mathematical formulation

There are some important formulations for evaluating the thermal performance and the thermal efficiency of PTCs. So in this section, some required formulas are presented. The efficiency of solar collectors is the ratio between the incident and useful energy. Both quantitative and qualitative surveys of energy can be carried out by the energy and exergy analysis of the systems.

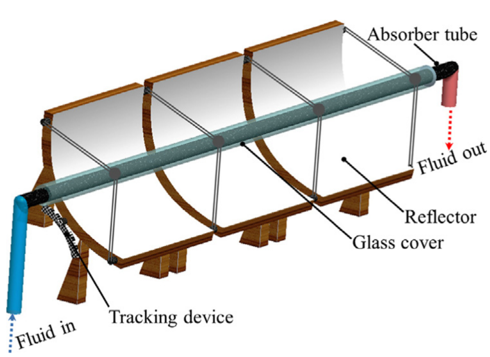

Fig. 1. Schematic diagram of a parabolic trough collector [5].

2.1. Thermal performance

Under a steady state condition, the thermal efficiency of a collector is given by:

$$\eta_{th} = \frac{Q_u}{A_{ap} I_D} \quad (1)$$

where Q_u is the useful energy transferred to the heat transfer fluid:

$$Q_u = \dot{m} C_{p,f} (T_{out} - T_{in}) \quad (2)$$

The thermal performance (η) is another important parameter to determine the effectiveness of heat transfer enhancement methods. This parameter evaluates the flow enhancement [6].

$$\eta = (Nu/Nu_p)/(f/f_p)^{1/3} \quad (3)$$

The thermal performance shows the improvement of the Nusselt number versus the friction factor variation.

The Nusselt number can be calculated by [6]:

$$Nu = \frac{hD_{ri}}{k} \quad (4)$$

where h is the heat transfer coefficient between fluid and an absorber tube.

$$h = \frac{Q_u}{(\pi.\ D_{ri}.\ L).\ (T_r - T_{fm})} \quad (5)$$

And,

$$T_{fm} = \frac{T_{in} + T_{out}}{2} \quad (6)$$

The friction factor demonstrates the pressure drop along the tube [6]: