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Hybrid optimization algorithm for thermal analysis in a solar parabolic trough collector based on nanofluid

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ABSTRACT

In recent years, many research works focused on improving and reducing the cost of solar collectors. This paper focuses upon the development of an efficient modeling and optimization of solar collector. The approach adopted in modeling utilizes a parabolic trough collector absorber tube with non-uniform heat flux, fully developed mixed convection flow and Al_2O_3/synthetic oil as a base fluid. Optimization of thermal analysis in a solar trough collector using nanofluid is non-convex, non-linear and computationally intensive process. In order to overcome these difficulties, a hybrid optimization method involving GA (genetic algorithm) and SQP (sequential quadratic programming) is introduced in the optimization process. The optimization problem used in this study involves maximization of a non-dimensional correlation consisting of Nusselt number and pressure drop with Reynolds and Richardson number which are used as design constraints. The methodology implemented within an integrated environment involving Matlab, Gambit and Fluent. The results obtained show that heat transfer enhancement has a direct relationship with the nanoparticle concentration ratio whereas it has inverse relationship with the operational temperature. In addition, the results show that the proposed methodology provides an effective way of solving thermal analysis in a solar parabolic trough collectors based on simulation models.

1. Introduction

In recent years, there has been an increasing need in using renewable energy. Renewable energy is sustainable, produces zero or few greenhouse gas emissions and will never run out, so has minimal impact on the environment. Solar energy is the oldest energy source ever used, with a high amount of supply. PTCs (Parabolic trough collectors) are one of the main solar heat collected elements, which can be applied to light structure and low-cost systems for producing heat up to 400 °C. However, cost is one of the major factors limiting development of trough collectors. Improving the thermal performance of solar collector systems can in part alleviate this problem. Therefore, optimal design of solar collector systems has become more important research issues in solar energy. The methodology presented in this paper involves modeling and optimization of parabolic trough collectors using nanofluid. There has been a limited research work reported on modeling of parabolic trough collector absorber tube under the non-uniform heat flux [1,2]. For example, Chenge et al. [3] modeled and analyzed parabolic trough solar collectors with a detailed Monte Carlo ray-tracing optical model, which demonstrated main characteristics and optical performance of the PTC systems. Ouagueda et al. [4] has estimated the performance of solar PTC under the climate conditions in the country of Algeria. In this work, HCE (heat collector element) is divided into several segments. The heat balance is applied to each segment over the section of the solar receiver. This work investigated the thermal performance of different HTF (heat transfer fluids) and the heat gains were compared under the topographical and climatic conditions.

There is different ways to improve the performance of PTC and in some studies. Using nanofluid as a working fluid in solar systems is a novel approach to increase the efficiency of solar systems. Some theoretical and experimental studies have been carried out on the effect of utilizing nanofluid in the solar collector system [5–10].

Mahian et al. [11] studied entropy generation of Al_2O_3/water nanofluid flow in a flat plate solar collector. In this work, different

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nanoparticle sizes and thermo-physical models for both smooth and rough tubes are considered. They found that the Nusselt number enhancement has a direct relationship with nanoparticle size and inverse relationship with concentration ratio. Whereas the heat transfer coefficient and the outlet temperature have an opposite trend compared to the Nusselt number. Also they indicated the value of the heat transfer coefficient and Nusselt number are affected by different models of thermo-physical properties; whilst the models have no significant effect on the outlet temperature and entropy generation. Yousefi et al. [12] used $Al_2O_3-H_2O$ nanofluid as a working fluid in a flat-plate solar collector experimentally, in which 28.3% enhancement of efficiency for 0.2 wt% nanoparticle concentration has been observed. Kasaeian et al. [13] studied the heat transfer enhancement for Al_2O_3/synthetic oil nanofluid in a parabolic trough collector tube numerically. This work shows that the heat transfer coefficient is increased as the concentration of the nanoparticles in the base fluid is increased. Khullar et al. [14] studied theoretically the nanofluid usage in a concentrating parabolic solar collector and the results of this work demonstrate 5–10% higher efficiency as compared to the conventional models. Waghole et al. [15] carried out an experimental work on PTC with and without twisted tape using silver/water nanofluid, the results of this work show that Nussult Number, friction factor and enhancement efficiency are 1.25–2.10 times, 1.0–1.75 times and 135%–205%, respectively, over plain absorber of PTC. Sokhansefat et al. [16] investigated heat transfer enhancement in parabolic trough collector tube using Al_2O_3/synthetic oil nanofluid, and demonstrated the enhancement in heat transfer coefficient caused by nanoparticles decreases whilst the operational temperature of the absorber tube increases.

Recently, some research works have been carried out to optimize the performance of solar collector systems [17–19]. Qibin et al. [20] developed the LSSVM (least squares support vector machine) approach to model and optimize the parabolic trough solar collector system and the results show solar collector efficiency increases with the increase of the solar flux and the flow rate of the heat transfer fluid; whereas with increasing the inlet temperature, the efficiency is decreased. Cheng et al. [21] presented detailed parameter study on the comprehensive characteristics and photothermal performance of a PTC system. In this research work, the relations between the main designed parameters and some important variables of the reflector were presented theoretically. Also the effects of these parameters on the comprehensive characteristics and performance were numerically studied. Risi et al. [22] modeled and improved TPTC (transparent parabolic through collector) working with gas-based nanofluid. In this study solar thermal efficiency is considered as an objective function with four design variables and a genetic algorithm has been used for optimization process. The result of this work shows that the maximum TPTC solar to thermal efficiency is 62.5%. Silvaa et al. [23] developed a thermo-economic design optimization procedure of a parabolic trough solar plant with hybrid algorithms. The design variables considered in this study are the number of collectors in series, number of collector rows, row spacing and storage volume. Multi-objective optimization approach is proposed to analyze the design problem. Two functions including payback time and life cycle savings are considered as the objective functions. In this study, a levelized cost of energy of 5 c€/kWh and 8 years payback time was illustrated.

The present work presents an efficient methodology for optimization and thermal analysis in a solar PTC based on nanofluid. The proposed methodology involves two main stages. First stage involves modeling of trough collector absorber tube and the effects of nanoparticle concentration on mixed convection heat transfer rate of the nanofluid in a fully-developed turbulent flow. Al_2O_3/synthetic oil was used as the heat transfer fluid and Gambit software was utilized to generate mesh and define types of the boundary conditions. The flow solver of Fluent was used to solve the problem. In the second stage, a hybrid optimization algorithm involving GA (genetic algorithm) and SQP (sequential quadratic programming) is introduced.

2. Methodology

The proposed methodology consists of two main stages including modeling and optimization which are described in the following sections.

2.1. Modeling of the parabolic trough collector absorber tube using Al_2O_3/synthetic oil as a base nanofluid

In this section a trough collector absorber tube is modeled and the effects of nanoparticle concentration on the mixed convection heat transfer rate of the nanofluid in a fully-developed turbulent flow are studied. The heat flux is non-uniform on the outer surface of the inner absorber tube. The modeling was done according to the LS-2 PTC, tested on the AZTRAK rotating test platform at SNL by Dudley et al. [24]. Al_2O_3/synthetic oil was considered as the heat transfer working fluid and all thermo-physical properties of the nanoparticle and base fluid were considered dependent on the operational temperature.

The thermo-physical properties of the base fluid (synthetic oil) and the nanoparticles (Al_2O_3) including density, viscosity, thermal conductivity, and specific heat were considered as varied with the operational temperature [16]. The properties of the nanofluid are dependent on the thermo-physical properties of the base fluid, volume concentration ratio of nanoparticle and temperature. In the current study two models are used for the nanofluid study for modeling of thermal conductivity, viscosity and specific heat. These models are presentment in Table 1. Since there is no experimental data on the viscosity of Al_2O_3/oil, then we had to use the experimental data of SiO_2/oil nanofluid. As known, the most effective parameter in the viscosity of nanofluids is the size of nanoparticles, since the size of nanoparticles in our work is close to size of particles in Ref. [29], then it is reasonable to use this relation. Also density of nanofluid is determined by the following equation [25].

$$\rho_{eff} = (1-\phi)\rho_f + \phi\rho_s \tag{1}$$

In all of the correlations, *f*, s, and *eff* correspond to the basefluid, nanoparticle and nanofluid, respectively, and ϕ is the volumetric concentration of Al_2O_3 in the nanofluid. The numerical values of these properties for the operational temperatures of 300 K and 500 K in two concentration ratios are provided in Table 2.

The absorber tube is 7.8 m (L) long and 0.07 m (D_a) in diameter according to the LS-2 parabolic trough collector [22]. The flow is assumed to be fully-developed turbulent mixed convection. Also the solar energy flux distribution is considered non-uniform and gravitational force is exerted in the y direction. As a case study, Al_2O_3/synthetic oil was used as HTF in the collector field and nanofluid flow was considered single phase flow. The schematic diagram of the absorber tube and heat flux distribution is shown in Fig. 1.

The solar energy flux distribution on the outer wall of the inner absorber tube has been calculated by the developed MCRT (Monte Carlo Ray Trace) code [1]. The result of this code, which is demonstrated in Fig. 2, was used in this study. Then this flux is treated as the heat flux boundary for the simulation model in the Fluent software with a UDF code.

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