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Optimization of a solar collector with evacuated tubes using the simulated annealing and computational fluid dynamics

J. Arturo Alfaro-Ayala[a,*], Oscar A. López-Núñez[a], F.I. Gómez-Castro[a], J.J. Ramírez-Minguela[a], A.R. Uribe-Ramírez[a], J.M. Belman-Flores[b], Sergio Cano-Andrade[b]

[a] Department of Chemical Engineering, University of Guanajuato, DCNE, Col. Noria Alta s/n, C.P. 36050 Guanajuato, Gto., Mexico
[b] Department of Mechanical Engineering, University of Guanajuato, DICIS, Carretera Salamanca-Valle de Santiago km. 3.5 + 1.8, Comunidad de Palo Blanco, C.P. 36885 Salamanca, Gto., Mexico

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ABSTRACT

In this work, the optimization of a low temperature, water-in-glass, evacuated tubes solar collector is presented. The process of optimization combined the simulated annealing method and a computational fluid dynamics model. The numerical study was carried out in three dimensions, steady-state and laminar regime. A design of experiments study via computational fluid dynamics was carried out with two levels and five parameters, 2^5, the parameters with significance in the performance of the collector were found from a commercial collector. This collector was used as base case in the process of optimization. In the optimization process, the absorber area was analyzed under three different cases because of the combination of geometrical parameters: length, diameter and number of tubes. Thus, 259 different collector geometries were constructed and modeled. Results from the design of experiments showed that the significant parameters on the thermal performance of the solar collector are: the diameter of the tubes, the absorber area, and the mass flow rate. Results of the optimization process showed that the minimum absorber area for an optimal geometry is 2.49 m^2, which is 19.4% lower than the commercial geometry considering the same outlet temperature. The diameter of the tubes increased around 30%, the length of the tubes decreased 40%, the cost of the optimal geometry and the number of evacuated tubes decreased 38.9% and the thermal efficiency increased 26.3%, compared to the commercial geometry. The results of this work can be helpful in further specific applications where the maximum performance and the minimum costs are important, such as: the design of low temperature, water-in-glass, evacuated tubes solar collector networks for heating water in swimming pools, buildings, hospitals and industries.

1. Introduction

Solar energy is the most appropriate source that could satisfy the growing demand for energy worldwide [1]. It has an important effect in the reduction of the greenhouse gas emissions [2] and can be converted directly into thermal energy by using solar collectors. These equipments collect energy from the solar radiation by absorbing and transferring it to a working fluid. This is the case of the water-in-glass evacuated tubes solar collectors (ETSC), which remain stationary regardless of the sun's position and are suitable for low temperature applications (lower than 100 °C). The water-in-glass tubes are made of borosilicate glass, each one consisting of two concentrical tubes: the inner tube is coated with a selective coating, while the outer tube is transparent. Between the inner and the outer tubes, there is an annular space where the air is evacuated at a vacuum pressure. This vacuum leads to an important improvement of the thermal performance of these solar collectors due to the reduction of heat losses. Low temperature water-in-glass ETSCs are generally used in serial and/or parallel networks to satisfy a duty of warm water in pools, buildings or industrial processes [3]. An adequate selection of the equipment through the optimized ETSCs would decrease the costs of the networks and the space occupied by them.

The thermal performance and efficiency of the water-in-glass ETSC by means of experimental and theoretical methods have been reported in the literature. Experimental works of ETSCs were focused to obtain a better thermal performance: Recalde et al. [4] analyzed the behavior of the natural circulation of the water inside of a glass evacuated tubes solar collector under the action of the solar radiation in the Equator Andean high lands, the data collected during the experiments showed that the highest value of the water temperature is obtained with small inclinations, it occured due to the increase incidence area of solar radiation and captured energy. Tang and Yang [5] carried out an experimental work considering different tilt angles to find the thermal

* Corresponding author.
E-mail address: ja.alfaroayala@ugto.mx (J.A. Alfaro-Ayala).

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Nomenclature

A_a	absorber area, m^2
c	specific heat of water, $J\,kg^{-1}\,°C^{-1}$
c_b	specific heat of borosilicate glass, $J\,kg^{-1}\,°C^{-1}$
c_p	specific heat of polyurethane, $J\,kg^{-1}\,°C^{-1}$
G_D	direct radiation, $W\,m^{-2}$
G_d	diffuse radiation, $W\,m^{-2}$
G_r	reflected radiation, $W\,m^{-2}$
G	total radiation, $W\,m^{-2}$
G	incident radiation = direction-integrated intensity
g_y	gravity in y-direction, $m\,s^{-2}$
h	convective heat transfer coefficient, $W\,m^{-2}\,°C^{-1}$
I_η	radiation intensity, $W\,m^{-2}\,sr^{-1}$
j_η	emission coefficient, $W\,m^{-3}\,sr^{-1}$
k	conductivity, $W/m\,°C^{-1}$
$\dot{m}$	mass flow rate, $kg\,s^{-1}$
N_{tub}	number of tubes, dimensionless
P,p	pressure, Pa
q''	solar heat flux, $W\,m^{-2}$
q_R	radiative flux, $W\,m^{-2}$
$\hat{s}$	unit vector into a given direction, dimensionless
$\hat{s}_i$	direction vector, dimensionless
T	temperature, °C
T_{amb}	ambient temperature, °C
T_{in}	inlet temperature, °C
T_{outCFD}	CFD outlet temperature, °C
T_{outexp}	experimental outlet temperature, °C
v	velocity vector, m/s
Greek letters	
η	wave number, m^{-1}
η_{ther}	thermal efficiency, dimensionless
κ_η, κ	absorption coefficient, m^{-1}
μ	dynamic viscosity, Pa s
ρ	density, $kg\,m^{-3}$
ρ_g	ground reflectivity, dimensionless
$\sigma_{s\eta}$	scattering coefficient, m^{-1}
σ	Stefan–Boltzmann constant, $W\,m^{-2}\,K^{-4}$
Φ_η	scattering phase function, dimensionless
Ω_i	incident solid angle, sr

performance of the collector, it was concluded that a higher thermal performance is obtained with the optimal tilt angle and it dependes of the specific geographical location.

On the other hand, computational fluid dynamics (CFD) works were reported in the literature. Wang et al. [6] studied a novel design of a low temperature solar collector by using CFD. The effects of parameters, such as the tilt angle of the solar collector, the mass flow rate and the air gap distance, on the thermal performance and efficiency of the collector were obtained. Yao et al. [7] made CFD numerical simulations with a twist tape inserted inside the evacuated tubes. It was concluded that the twist tape insertions allowed having a higher dissipation of mechanical energy and a temperature field more uniform to improve the thermal performance of the equipment. Essa and Mostafa [8] showed the ability of the CFD modeling by using the radiative transfer equation (RTE). The weather conditions were set up in the simulations by considering the location, the date and the corresponding hours of a day. It was concluded that the use of CFD can be considered as a powerful tool for calculating the thermal performance of the low temperature solar collector under real climate conditions.

In the review of the literature, just few works were focused on obtaining an optimum solar collector. Cheng et al. [9] applied the particle swarm optimization (PSO) method to find the optimal performance of optical parameters of a high temperature parabolic solar collector. Mohammad et al. [10] presented the optimization of the thermal performance of a high temperature parabolic solar collector with a nanofluid. The process of optimization was carried out by the genetic algorithms (GA). The results showed that the increase of heat transfer is directly related to the amount of nano-particles. Facão [11] made the optimization of the geometry and fluid flow distribution to a flat plate solar collector by the use of Nelder-Mead simplex algorithm. It was concluded that the manifold of the outlet of the flat plate solar collector should have a bigger size than the manifold of the inlet to obtain a better performance. Kulkarni et al. [12] applied genetic algorithms (GA) with CFD techniques to a solar air heater. The maximum transfer of heat and the minimum pressure drop were found. The optimal configuration of the geometry and the thermal performance were obtained.

On the other hand, some works applied CFD modeling in the design of experiments (DOE) to obtain the parameters that had significance in the performance of the case study. Sant'Anna et al. [13] applied CFD modeling and a DOE study with a factorial design of 2^3 to find that the diameter of the biomass particles had significance in the bubbling fluidization condition. Shojaee et al. [14] applied a two-level factorial design and four parameters, 2^4. The parameters that had significance in a mass transfer study into an electronic enclosure were obtained. However, a work that obtains the significant parameters of a low temperature, water-in-glass, evacuated tubes solar collector through using the computational fluid dynamics in the design of experiments cannot be found in the literature. Also, the literature review indicated that few works were focused on the process of optimization of solar collectors and there is not a study focused in the optimization of low temperature, water-in-glass, evacuated tubes solar collectors. Moreover, the optimization of a low temperature, water-in-glass, evacuated tubes solar collector combining different techniques such as design of experiments, simulated annealing and computational fluid dynamics is not reported.

In this work, an optimization process is applied to the geometry of a low temperature, water-in-glass, evacuated tubes solar collector. The geometrical and operational parameters with significance in the thermal performance of the evacuated tubes solar collector are obtained with the help of the computational fluid dynamics in a design of experiments study. The combination of the simulated annealing method and the computational fluid dynamics modeling allow finding the optimal geometry and optimal thermal and hydraulic performance of the solar collector. Integrating these methods, it is possible to consider details in the geometrical and operational parameters, such as: diameter, length, absorber area and number of the tubes and mass flow rate respectively, which are of outmost importance in the behavior of the fluid flow and the transfer of heat. The numerical study was carried out in three dimensions, steady-state and laminar regime. The design of experiments study via computational fluid dynamics was carried out with two levels and five parameters, 2^5, the parameters with significance in the performance of the collector were found from a commercial collector. This collector was used as base case in the process of optimization. In the optimization process, the absorber area was analyzed under three different cases because of the combination of geometrical parameters: length, diameter and number of tubes. Thus, 259 different collector geometries were constructed and modeled. Comparison of the thermal performance between the optimal geometry and the commercial geometry was carried out for different experimental test (mass flow rate, inlet temperature, ambient temperature and solar radiation). The optimal geometry of the low temperature, evacuated tubes, solar collector achieves higher thermal performance and lower costs than the commercial geometry used as reference at any operational and weather conditions.