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Comparison of the thermo-hydraulic performance and the entropy generation rate for two types of low temperature solar collectors using CFD

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ABSTRACT

In this work, a comparison of the thermo-hydraulic performance and the entropy generation rate for two different types of low temperature solar collectors: flat plate solar collector (FPC) and water-in-glass evacuated tube solar collector (ETC), is addressed. The absorber area for both solar collectors were considered to be equal for a reliable comparison. The operation of the solar collectors was simulated under different volumetric flow rates and solar radiation values for the state of Guanajuato in Mexico. The volumetric flow rate for both collectors ranged from 1 to 9 L/min. The variation of the solar radiation was based on: (1) the solar radiation taken from several experimental tests reported elsewhere, (2) the month with the lowest average solar radiation in one year, (3) the average solar radiation of one year and (4) the month with the highest average solar radiation in one year. The buoyancy effects were considered in the CFD simulations using the Boussinesq approximation (BA) model. The distribution profiles of temperature, pressure, and velocity inside the tubes of the solar collectors, along with the local entropy generation rate distribution due to heat transfer and the fluid viscosity, are shown in detail. The results show a better thermal performance for the solar water-in-glass evacuated tube collector (ETC) than for the flat plate solar collector (FPC) at low flow rates (under 3.0 L/min). The outlet temperature reached is similar in both collectors for volumetric flow rates higher than 3.0 L/min. The analysis of the entropy generation rate shows that the generation due to the transfer of heat is higher for the ETC than for the FPC, and this contribution is up to 10% of the total entropy generation rate; on the other hand, the generation rate due to the fluid viscosity is higher for the FPC than the ETC at high volumetric flow rates (above 3.5 L/min), however, this contribution is negligible. Finally, the total entropy generation rate is higher for the FPC than the ETC at low volumetric flow rates (below 3.0 L/min) and this is increased if the solar radiation increases.

1. Introduction

Nowadays, most scientific efforts are focused on reducing the consumption of fossil fuels such as coal, oil, and natural gas, to reduce the effect of greenhouse gases (GHG) released into the atmosphere. The largest source of renewable energy available on earth is solar energy, since it receives millions of watts of energy every day from solar radiation. However, only a fraction of the solar energy, in the form of daylight and photosynthesis, is used in the world. One third of the solar radiation received is reflected back into space and the rest is absorbed by the earth, the oceans, and the clouds (Wei, 2010). Therefore, it is very reasonable to collect solar energy to convert into heating or cooling. Processes that use solar energy have a minimal impact on the environment.

Besides environmental awareness, dwindling of traditional energy sources has led to solar energy being the most suitable energy source to meet the growing demand for energy worldwide. Researchers have investigated and developed technologies on how to collect solar energy to serve humanity and are still considering the use of innovative technologies to maximize the collection and utilization of solar energy (Sabiha et al., 2015). Among these technologies, the solar water heathers (SWH) and collectors have been attracting much attention due to the direct conversion of the solar energy into thermal energy. The absorbed solar radiation is transformed into heat and transferred to the heating processes by a fluid, commonly water.

There are two common types of stationary collectors: Flat plate

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Nomenclature

A_c	absorber area of the solar collector, m^2
c	specific heat, $J\,kg^{-1}\,K^{-1}$
g	gravity, $m\,s^{-2}$
I_T	incident solar energy per unit area, $W\,m^{-2}$
$\overrightarrow{J_q}$	heat flux, $W\,m^{-2}\,K^{-1}$
$\overrightarrow{J_s}$	entropy flux, $W\,m^{-2}\,K^{-1}$
k	conductivity, $W\,m^{-1}\,K^{-1}$
$\dot{m}$	mass flow rate, $kg\,s^{-1}$
P	pressure, Pa
$\dot{Q}_{useful}$	useful heat, W
$\dot{Q}_{loss}$	heat loss, W
$\dot{Q}_{sun,in}$	energy gain rate, W
S_i	global entropy generation rate for each contribution, $W\,K^{-1}$
S_q	heat loss entropy generation rate, $W\,K^{-1}$
S_{total}	total entropy generation rate, $W\,K^{-1}$
s	specific entropy, $J\,kg^{-1}\,K^{-1}$
s_p	entropy generation rate, $W\,K^{-1}\,m^{-3}$
s_μ	fluid friction entropy generation rate, $W\,K^{-1}\,m^{-3}$
s_h	heat transfer entropy generation rate, $W\,K^{-1}\,m^{-3}$
T	temperature, K
T_{env}	temperature of the environment, K
T_{in}	temperature at the inlet of the solar collector, K
T_{out}	temperature at the outlet of the solar collector, K
t	time, s
u_x, u_y, u_z	velocity component, m/s

Greek letters

β	volumetric thermal expansion coefficient, K^{-1}
μ	dynamic viscosity, Pa s
ρ	density, $kg\,m^{-3}$

collectors (FPCs) and evacuated tube collectors (ETCs). FPCs and ETCs are the most widely used collectors for small-scale heating water applications (Ayompe et al., 2011). The thermal performance of FPC is strongly related to the flow distribution through the absorber tubes (Duffie and Beckman, 1991). They contribute to satisfy the heat demand at low temperature, such as heating of water for use in houses, buildings, and swimming pools. The operation of a FPCs is well known, even though it is still being paid much attention to solar collectors in order to increase the efficiency and reduce the costs (Del Col et al., 2013). Several studies focused on the thermal efficiency of FPCs (Matrawy and Farkas, 1997; Rommel and Moock, 1997; Groenhout et al., 2002; Minn et al., 2002; Alvarez et al., 2010; Akhtar and Mullick, 2007; Diego-Ayala and Carrillo, 2016).

Among the different types of stationary solar collectors, the evacuated-tube solar collectors (ETCs) present better thermal performance and lower costs than conventional flat plate solar collectors (Tang et al., 2011; Louise and Simon, 2007). A water-in-glass evacuated tubes solar collector consists of a set of glass tubes connected to a manifold or tank. Each tube is surrounded by a second glass tube of a larger diameter. The annular space between the tubes is evacuated to minimize the heat losses. The working fluid, generally water, flows from the tank to the tubes, captures heat, and then flows back into the tank by a natural circulation mechanism (Morrison et al., 2004). The evaluation of the overall performance of the solar collectors is usually carried out by trial and error, according to national or international standards (ASHRAE, 2010; Hill and Streed, 1976; Proctor, 1984). These works led to the proposal of several empirical correlations with the aim of predicting the overall performance and efficiency under different weather conditions.

Several experimental studies have been carried out to evaluate the thermal performance of solar collectors. Azad (2018) presented a comparative study of the experimental analysis of two heat pipe solar collectors with different number of heat pipes and a flow-through collector. The three collectors were designed, constructed, and tested side-by-side under various environmental conditions and the thermal efficiency was obtained. He proposed two methods for increasing the efficiency of heat pipe collectors: the first is by increasing the number of heat pipes and the second is by increasing the effective absorber area. Iranmanesh et al. (2017) investigated experimentally the effect of graphene nanoplatelets with different concentrations on the thermal performance of evacuated tube solar water heaters. The thermal efficiency tests on the solar heaters were carried out varying the volumetric flow rate. Their results indicated that the thermal energy gain increases as the mass percentage of nanoparticles also increases, reaching a higher fluid outlet temperature when graphene nanosheets were used. Sharafeldin et al. (2017) investigated the effects of using WO_3/water nanofluids (with different volume fractions) and different mass flux rates on the thermal performance of a flat plate solar collector operating under Budapest, Hungary weather conditions. Their results showed that, by adding WO_3 nanoparticles to the water, the efficiency of the solar collector improves. Some experimental studies have also been carried out to evaluate the thermal performance of evacuated tube solar collectors in order to compare them with their flat plate counterparts, using different absorber collector areas. Zambolin and Del Col (2010) conducted an experimental analysis of the thermal performance of a flat plate collector and an evacuated tube solar collector in stationary, standard and daily conditions on the terrace roof of the *Dipartamento di Fisica Tecnica* at the University of Padova, Padova, Italy, considering an aperture area of $4.76\,m^2$ and $3.5\,m^2$, respectively. They characterized and compared the daily energy performance of these collectors. Ayompe et al. (2011) compared the energy performance of two solar collectors; a FPC with an absorber area of $4\,m^2$ and a ETC with an absorber area of $3\,m^2$. The study considered constant weather conditions (Dublin, Ireland on daily, monthly and yearly basis) to test the solar collectors. They obtained the system efficiencies and the average collector efficiencies for the FPC and ETC.

Numerical techniques have been also used to investigate the thermal performance of solar collectors and to find possible ways to improve existing designs of FPCs and ETCs. The analysis is generally based on operating and design parameters. Studies have shown the effect on the thermal performance of solar collector under various parameters, such as solar radiation, inclination angle, ambient conditions, water inlet temperature, air flow rate, etc. (Hayek, 2009; Pandey and Chaurasiya, 2017; Cadafalch, 2009; Molero Villar et al., 2009; Herrero Martín et al., 2011; Deng et al., 2016; Zhang et al., 2014; Fernández and Deste, 2013; Hayek et al., 2011; Chow et al., 2011; Hazami et al., 2013; Morrison et al., 1984; Tang et al., 2011). Selmi et al. (2008) showed that the prediction of fluid flow and heat transfer in a FPC via computational simulation using a simplified geometry of the solar collector is complex and the number of research works on this subject is quite low. Tagliafico et al. (2014) presented a review on the use of CFD tools for the study of flat-plate solar collectors. The reported works reported good agreement with experimental data. It was concluded that CFD numerical simulations are useful in identifying ways to improve efficiency of solar collectors. Moreover, the use of CFD numerical techniques to elucidate the thermal and hydraulic performance of evacuated tube solar collectors is scarce, and some of the simulation reports consider only a part of the geometry under study (simplified to one tube) (Morrison et al., 2004; Morrison et al., 2005; Budihardjo et al., 2007; Waheed et al., 2012; Hayek, 2009) due to the required computational power; therefore, the use of real dimensions in simulations is scare (Arturo Alfaro-Ayala et al., 2015).

Besides, works based on the second-law of thermodynamics are also