Thermal behavior of a flat-plate direct absorption with water-nanohorn mixture

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Abstract. A numerical analysis on a two-dimensional steady state forced convection inside a solar collector with direct absorption due to a nanofluid composed of water and nanoparticles of carbon nanohorns is carried out. The analysis allows to provide the main fluid flow and thermal characteristics of a simple flat solar collector with a distance between the glass and the collecting plate of 1.2 mm and a length of 1.0 m. The solar collector presents heat losses from the upper wall towards the ambient by an external surface heat transfer coefficient. The governing flow equations for the nanofluid are written assuming the single-phase flow and the heat transfer due to the radiation, for the local absorption of nanoparticles, is evaluated by the non-grey discrete ordinates method. The carbon nanohorns optical and thermal properties are estimated by the data available in literature. The finite volume method is used to solve the problem and the results are carried out employing the ANSYS-FLUENT code. The results are given in terms of temperature and velocity fields and transversal profiles inside the channel for different values of mass flow rates, solar irradiance, volumetric nanoparticle concentrations and assigned values of external surface heat transfer coefficient and temperature.

1. Introduction
The need to reduce the energy consumption from fossil fuel is becoming an important task to reduce the environmental damage and earth warming. The renewable energy and particularly the solar energy can be a useful solution to reduce the fossil fuel use as energy resource. Different ad various solutions are available to employ the solar energy and nanotechnology applied to the solar collector systems is significantly developing due to the possible heat transfer enhancement [1]. In fact, the application of nanofluids is rapidly growing in the flat plate solar collectors due to its improved thermal conductivity respect to the pure water and direct absorbing of solar radiation [2].

A pioneering investigation on direct-absorption solar collectors, DASCs, was experimentally accomplished in [3]. A semi-transparent tube was the solar collector and the working fluid was a mixture of water and India ink with a concentration of 3.0 g/l. The experimental results pointed out an increase in thermal performance but the degradation of the mixture due to the sunlight exposure was significant. One of the first study on the use of nanofluids inside a direct-absorption solar collector was numerically carried out in [4]. The study in two-dimensional coupled radiative-convective model was accomplished to take into account both the absorption and the scattering of incident solar energy. A comparison with a surface flat plate collector showed improved the thermal efficiency of the system. The main studies on the use of nano fluids in solar collectors are reviewed in [1,2,5,6]. The analysis on theoretical models and optical behaviors for DASCs with nanofluids was given in [5]. A
review on investigations related to the effect of various parameters and the optimum working condition is accomplished in [2]. A survey on numerical methods employed in the simulation of DASCs with nanofluids for different geometries was provided in [6]. In the review presented in [1], the DASCs at low temperature were analysed considering the design and operating variables effects on fluid flow and thermal behaviors.

A numerical investigation of DASC with single wall carbon nanohorns, SWCNHs, was realized in [7]. The results indicated an increase of 17% with respect to use of water in the flat plate collector. The components of a DASC were systematically analyses to determine their theoretical radiative limitations in [8]. The concept of “nanofluid-based selective direct absorption collector” was introduced to allow the evaluation of the theoretical limitations. A direct absorption solar collector with a parabolic trough solar concentrator was numerically investigated in [9] employing a mixture of water and SWCNHs. A DASC with SWCNHs in pure water was numerically simulated in [10] by lattice Boltzmann method. The effect of the collecting plate position was discussed. The results showed that the absorber plate determined an improvement of the collector performance particularly in the pure water case. A numerical study on two configurations of direct volumetric absorption collector with carbon nanohorns was proposed in [11].

It seems that the knowledge on the thermal performances of direct solar absorption flat plate collectors using nanofluid composed with water and carbon nanohorns presents some lack. In this paper a numerical study on a DASC with a mixture of water and carbon nanohorns is carried out to evaluate the thermal efficiency of the flat solar collector for different values of the absorption coefficient of the plate, mass flow rate and inlet temperature.

2. Problem description and numerical model
A two-dimensional (2D) geometry, Fig. 1, of the direct absorption flat-plate solar collector is considered with SWCNH-water nanofluid. The solar collector is made up two parallel plates which the height W = 0.0012 m and the length L = 1 m. The top of the collector is covered with a transparent glass with transmissivity $\tau=0.9$ and the bottom plate is considered be a reflector and adiabatic. The solar irradiation impinges orthogonally on the top surface glass plate and diffuses from top to bottom through the volume of the nanofluid.

The forced flow inside the collector is assumed to be laminar, incompressible, and steady state. All thermophysical properties are temperature independent and the viscous dissipation is neglected. The considered concentrations of the carbon nanohorns in base fluid (water) are: 0 g/l (pure water), 0.001g/l, 0.002 g/l, 0.004g/l, 0.010 g/l, 0.020 g/l and 0.050 g/l. The extinction coefficients as function wavelength, given by Sani et al. [12], for small concentration of SWCNH in water is shown in Fig. 2.

Boundary conditions of the problem: (1) at inlet section are assumed the temperature equal to 288.15 K, 293.15 K and 298.15 K and the mass flow rate equal to 0.1 and 0.2 kg/s; (2) at exit section the full developed flow is assumed; (3) the no-slip flow condition on all wall is considered and the adiabatic condition is assumed on the bottom plate.

The numerical simulations are performed using the Ansys-Fluent code. The Simple algorithm is considered to solve the coupled between pressure and velocity. In the energy and momentum equations, a second order upwind scheme and a central scheme is applied to discretize the convective and diffusive flux, respectively. The Discrete Ordinates (DO) radiation method is chosen to solve the radiation transfer equation (RTE). Convergence criteria are assumed to be equal to 10-5 for the continuity and the velocity components and equal to 10-8 for the energy equation.

3. Results and discussions
In the present work the thermal efficiency of the system was determined in different working conditions. We have determined the temperature profiles of the glass and lower surface, which has an emissivity coefficient equal to 0.1. The inlet temperatures considered are 288.15 K, 293.15 K, 298.15 K and a mass flow rate of 0.1 and 0.2 kg/s.
The evaluation of average temperature value at the collector outlet section allows to calculate the thermal efficiency of the system with the following relationship [13]:

\[
\eta = \frac{mc_p(T_{\text{out}} - T_{\text{in}})}{Q}
\]  

(1)

The efficiency values as a function of nanoparticle concentrations are given in Fig. 3, for three value of inlet temperature. The highest thermal efficiency is obtained for the temperature inlet equal to 288.15 K. Moreover, with the addition of more nanoparticles, more solar flux incident is expected to be absorbed by the working fluid and, consequently, the collector efficiency increases due to the increase of the outlet temperature. The increase is considerably higher at low concentrations due to the lower absorption at lower concentrations which increases as the concentration increases. The efficiency increase becomes lower at higher concentrations and it tends to an asymptotic value due to the increase of heat losses from the glass toward the external ambient. In Fig. 3, it is observed that the collector efficiency decreases as the inlet temperature increases because, at assigned external conditions, the heat losses increase.
The effect of the absorption of the lower surface is reported in Fig. 4, where the efficiency is given as a function of the concentration. Three emission coefficients are considered, 0.1, reflective surface, 0.5 and 1.0. It is observed that, for reflective bottom surface, the lowest values of the thermal efficiency are obtained at lower values of nanoparticles concentration, while the highest values are obtained with the highest concentrations of nanoparticles. On the other hand, if the lower surface is absorbent type, it is observed that the highest values of thermal efficiency are obtained at low concentrations, while the lowest values of thermal efficiency are obtained with high concentrations of nanoparticles.

Figure 3. Thermal efficiency as a function of inlet temperature and particle concentration.

Figure 4. Thermal efficiency as a function of the bottom emissivity and particle concentration.

4. Conclusions
In the present study, a direct absorption solar collector (DASC) utilizing SWCNH-nanofluids was investigated. A 2-D numerical model based on radiative heat transfer and energy equations was developed and implemented to predict the temperature distributions within the collector.

For a reflective bottom surface, the efficiency increases with increasing nanoparticle concentration. this efficiency increases as the normalized temperature tends to zero. however, as the absorption coefficient of the plate increases, the efficiency gain decreases with the increase in the concentration of nanoparticles, until the addition of this becomes deleterious to the efficiency itself, in the case of an ideal absorbent bottom surface. At higher temperatures, the heat loss to the ambient is higher which subsequently leads to an overall decrease in thermal efficiency, Thus, the collector thermal is increased by flow rate.

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