Numerical Investigation of Nanofluid-based Solar Collectors

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Abstract. Solar thermal collectors are applicable in the water heating or space conditioning systems. Due to the low efficiency of the conventional collectors, some suggestions have been presented for improvement in the collector efficiency. Adding nanoparticles to the working fluid in direct absorption solar collector, which has been recently proposed, leads to improvement in the working fluid thermal and optical properties such as thermal conductivity and absorption coefficient. This results certainly in collector efficiency enhancement. In this paper, the radiative transfer and energy equations are numerically solved. Due to laminar and fully developed flow in the collector, the velocity profile is assumed to be parabolic. As can be observed from the results, outlet temperature of collector is lower than that obtained using uniform velocity profile. Furthermore, a suspension of carbon nanohorns in the water is used as the working fluid in the model and its effect on the collector efficiency is investigated. It was found that the presence of carbon nanohorns increases the collector efficiency by about 17% compared to a conventional flat-plate collector. In comparison with the mixture of water and aluminium nanoparticles, a quite similar efficiency is obtained using very lower concentration of carbon nanohorns in the water.

1. Introduction

A drastic increase in energy consumption and global problems caused by fossil fuels such as climate change and greenhouse effect, are the main reasons of larger attention to renewable energies in the world. On the other hand, lack of fossil fuel sources and increased energy demand due to population growth, building and industries development leads to move faster toward alternative energies for more environmental friendly options.

One of the best alternative energy sources which can be used instead of fossil fuels is solar energy considering economical, environmental and safety concerns. Thus, in the last two decades, solar energy technologies have been continually developed for efficient collection and conversion of solar radiation to useful energy.

Conventional solar collectors suffer from many limitations, such as surface-based absorption of incident solar flux causing high heat losses and the low thermal properties of the working fluid. Therefore, an enhancement in the efficiency of solar harvesting devices is a basic challenge which requires great effort.

Direct Absorption Solar Collectors (DASC), initially proposed in 1970s by Minardi and Chuang [1], utilize the concept of volumetric-based absorption of solar radiation to improve the collector efficiency. They developed a direct collector that absorbed solar radiation by the black fluid (water with 3.0 g/l. India ink), which flows in transparent plastic tubing formed in an oval shape.

An approach to conquer other limitations of solar collectors (i.e. poor absorption and thermal properties of the working fluid) is to add small sized solid particles to the working fluid as an
absorbing medium, as proposed and studied originally by Hunt et al. [2] and Abdelrahman et al. [3]. It is believed that incident radiation scattering which is caused by small particles, leads to an increase in radiation absorption within the fluid and thus improvement in collector efficiency. On the other hand, other thermophysical properties of nanoparticles in colloidal suspensions such as thermal conductivity and convective heat and mass transfer (Prasher et al. [4] and Krishnamurthy et al. [5]) is enhanced; therefore, direct absorption receivers which apply particle-laden-fluid as working medium have a great potential for better harnessing solar radiation.

Another configuration for DASC was proposed by Arai et al. [6] as a “volume heat-trap” solar collector in which a “fine-particle semitransparent liquid suspension” (FPSS) is used as a heat storage fluid. Based on this concept, the complete model was developed by Kumar and Tien [7] which considered the interaction of radiative flux with convective transport in an absorbing, emitting, and scattering particulate-laden falling film without neglecting the flow field or scattering in the film, not assuming the properties to be spectrally constant.

Recently many researchers have investigated the effect of using nanofluids (a liquid-nanoparticle suspension) as the working fluid on the efficiency improvement of DASC. Tyagi et al. [8] have numerically evaluated the performance of a “nanofluid-based direct absorption collector” using aluminum nanoparticle suspensions in water. The efficiency enhancement of 10% was obtained using DASC in comparison to a conventional flat-plate collector. A schematic of direct absorption solar collectors is shown in Figure 1.

![Figure 1. Schematic of a direct absorption solar collector](image)

The radiation absorption characteristics of Ni nanoparticles are studied by Kameya and Hanamura [9]. Using spectroscopic transmission measurement and prediction process based on Mie theory, they found that the absorption coefficient of Ni-based nanofluid is much higher than that of base liquid. Because of very high thermal conductivity, the family of carbon-based nanostructured materials like carbon nanoparticles, nanotubes and nanohorns can be one of the best candidates for solar energy harvesting in collectors. Sani et al. [10] used the nanofluids based on the carbon nanohorns as direct sunlight absorbers in their work. With regard to promising thermal and optical properties of nanohorns, a considerably higher sunlight absorption and thermal conductivity than pure water is obtained.

A numerical investigation similar to Tyagi et al. [8] was conducted by Otanicar et al. [11] and the numerical results are validated by comparisons made with experimental data obtained from a micro solar collector. They have reported an increase in collector efficiency for nanofluids made from carbon nanotubes, graphite and silver of nanoparticles.
Veeraragavan et al. [12] presents an analytical model that studies the effect of heat loss, particle loading, solar concentration and channel height on collector efficiency. They have also determined an optimum receiver length where the total efficiency is maximized.

In this paper, a numerical investigation is performed to calculate the DASC efficiency. First, the results of model using variable velocity are compared with those of a model using uniform velocity. Then, the extinction coefficient of carbon nanohorns is calculated according to Lambert-Beer law for efficiency calculation of collector based on single wall carbon nanohorns (SWCNH) suspensions in water. As another part of this study, the effect of volume fraction and collector height on the efficiency is considered. Finally, the efficiency improvement by carbon nanohorns-based nanofluids in direct absorption solar collector is compared with a flat-plate collector and aluminium nanofluid-based DASC.

2. Mathematical model
The incident solar intensity neglecting atmospheric absorption is calculated using the blackbody relation given by Eq. (1):

$$I_{h\lambda}(\lambda, T) = \frac{2hc_0^2}{\lambda^5 \left[ \exp \left( \frac{hc_0}{\lambda k_B T} \right) - 1 \right]}$$

(1)

where $h$ is Planck’s constant, $k_B$ is the Boltzmann constant, and $c_0$ is the speed of light in a vacuum.

The radiative transfer equation (RTE), which accounts for the change of intensity as the radiation passes through an absorbing, emitting and scattering medium is written as [13]:

$$\frac{\partial i_{\lambda}}{\partial y} = -K_{\lambda} i_{\lambda} + a_{\lambda} i_{\lambda} + \frac{\sigma_{\lambda}}{4\pi} \int_{\omega_0}^{\pi} i_{\lambda}(y, \omega) \phi d\lambda d\omega$$

(2)

where $i$ is the incoming radiation after subtracting the reflected component, $\lambda$ is the wavelength, $\omega$ is solid angle, $K_{\lambda}$ is the extinction coefficient composed of the absorption coefficient $a_{\lambda}$ and the scattering coefficient $\sigma_{\lambda}$.

In this study, we utilize the Lambert-Beer law for calculation of carbon nanohorns-based nanofluid extinction coefficient $K(\lambda)$, which utilizes the spectral transmittance $T(\lambda)$:

$$T(\lambda) = e^{-K(\lambda)l}$$

(3)

where $l$ is the propagation length within the medium. In the current study, the spectral transmittance of carbon-nanohorns is obtained from the experimental work of Sani et al. [10].

In the current study, the following assumptions are made for numerical solution of RTE: the gain by emission is neglected because of low temperatures in the collector and the gain by incoming scattering is very small compare to the absorbed radiation due to the small size particle approximation (Rayleigh scattering). Under the assumptions, the second and third terms (augmentation by emission and incoming scattering) can be eliminated and thus, the equation of radiative transfer can be simplified as:

$$\frac{\partial i_{\lambda}}{\partial y} = -K_{\lambda} i_{\lambda}$$

(4)

The temperature distribution within the collector working fluid is obtained by solving steady state two-dimensional energy equation shown below:
\[
\rho c_p u(y) \frac{\partial T}{\partial x} = k_{\text{eff}} \frac{\partial^2 T}{\partial y^2} - \frac{\partial q_r}{\partial y}
\] (5)

where \( q_r \) is the radiative heat flux obtained from:

\[
q_r = 2\pi \int i_{\lambda} d\lambda
\] (6)

and \( u(y) \) is the flow velocity as a function of collector depth.

A schematic of computational domain of the solar collector is shown in Fig. 2. The boundary condition at the top surface of the collector was considered as convection heat transfer, whilst the bottom was considered as adiabatic.

The collector efficiency can be defined as:

\[
\eta = \frac{\int_0^h \rho u(y) [T_{\text{out}}(y) - T_{\text{in}}] dy}{G_T}
\] (7)

where \( T_{\text{in}} \) is the fluid inlet temperature and \( G_T \) is the incident solar flux on the collector.

Equations (2) and (4) were solved numerically using the forward difference implicit method and the results are compared with those provided by Tyagi et al. (2009) in Figure 3 for the same working conditions. As can be seen, the results of two models are in acceptable agreement.

### 3. Results and discussion

CNHs, which discovered in 1998 by Dr. Sumio Iijima's research group [17], have many advantages such as carbon nanotubes. For instance, it has huge surface areas and therefore can be fabricated with high purity. Also, unsimilar to carbon nanotubes (CNT), carbon nanohorns can be made in a simple way without using any catalyst. Another advantage of CNH is the better thermal property in absorbing radiation comprised with CNT [18].

In the earlier works [10, 18 and 19], the researchers studied the absorption and scattering properties of aqueous suspensions of single wall carbon nanohorns and calculated stored energy fraction for different concentrations. In this paper, the intention of the authors is to investigate the effect of carbon nanohorn-based nanofluid on the performance of direct absorption solar collector.

Fig. 3 shows the temperature distribution as a function of the normalized depth of the collector (y/H) and at various SWCNH concentrations. This plot shows that, as expected, the temperature of the fluid...
increases by increasing SWCNH concentration. Moreover, the change in temperature is not uniform. The temperature increase is the highest for the top layers and decreases with depth, because the maximum attenuation in the spectral intensity occurs in the top layers, and decreases along the depth of the collector.

**Figure 3.** Temperature distribution within the solar collector for the various concentration of SWCNH (g/l)
Figure 4. Collector efficiency for the various concentration of SWCNH (g/l)

The influence of SWCNH concentration on the collector efficiency is presented in Fig. 4. With the addition of more nanoparticles, more solar flux incident is expected to absorb and hence, the collector efficiency increases. This increase is considerably rapid at low concentrations and then, becomes slow at higher concentrations.

The variation of the collector efficiency versus height (H) is shown in Fig. 5. It is seen that by increasing collector height, its efficiency increases and finally reaches an asymptotic value of about 90%. This can be explained by the fact that more incident solar flux is attenuated across the greater depth and is absorbed by nanofluid which leads to higher temperature and thus higher solar collector efficiency.
To better understand the effect of height on the collector efficiency, the temperature contours for three heights are shown in Fig. 6. These contours indicate that more solar radiation is absorbed in bottom levels by increasing collector height; hence, the outlet temperatures are raised. In collector height of 5mm, about 95% of incoming solar radiation is absorbed. This result indicates that increasing collector height will be valuable only up to a certain limit, beyond which the increase in efficiency would be miniscule.
To highlight the comparison between our nanofluid-based collector model and the conventional one, the efficiency of these collectors is compared and the results are shown in Fig. 7. The efficiency improvement of about 0.8% is obtained by adding 0.02 g/l carbon nanohorns (h=5mm) to the base fluid (water) compare to a typical flat-plate collector. This increase is 9% and 17% for 0.05 g/l carbon nanohorns and collector heights 3 and 5 mm, respectively. This increase in the efficiency using carbon nanohorns shows the potential use of this nanofluid-based collector in solar heating systems.
For making comparison, the collector efficiency is plotted using carbon nanohorns- and aluminium nanoparticles-based nanofluid as the working fluid of DASC (results of Tyagi’s study) (Fig. 8). At the same collector height, a little difference (about 1%) is shown in the calculated efficiencies, whereas aluminium nanoparticles concentration in the water is very upper than to carbon nanohorns concentration. This represents that carbon nanohorns, the most recent in the family of carbon nanostructures, can play a very promising role in enhancing the DASC efficiency.
4. Conclusion
In this paper, a two-dimensional heat transfer model for analysis of nanofluid-based direct absorption solar collector was developed. The velocity profile between two plates of collector is assumed parabolic and its effect on the results is considered. It was found that the calculated outlet temperatures and efficiencies assuming constant velocity is higher than those obtained based on variable velocity. The performance of direct absorption solar collector is considered using the model with a mixture of carbon nanohorn and water as the working fluid. The effect of various parameters such as nanoparticle concentration and collector height on the efficiency was evaluated. The results show that the collector efficiency can be increased significantly by increasing height of the collector and the carbon nanohorns concentration, but only up to a certain limit, beyond which the increase in efficiency would be miniscule. Finally, the efficiency of the solar collectors utilizing aqueous suspension of carbon nanohorns (h=5mm, 0.05 g/l SWCNH concentration) is higher about 17% than that of a conventional flat-plate collector. At the same conditions, the collector performance can be better by adding nanohorns in proportion to aluminium nanoparticles to the base fluid.

Nomenclature

| Symbol | Description |
|--------|-------------|
| A      | Area (m²)   |
| a      | Absorption coefficient |
| c₀     | Speed of light (m s⁻¹) |
| cₚ     | Specific heat (J kg⁻¹ K⁻¹) |
| D      | Mean particle diameter (m) |
| fᵥ     | Particle volume fraction (%) |
| Gₚ     | Incident solar flux (W m⁻²) |
| h      | Planck’s constant (J s) |
| H      | Thickness of solar collector (m) |
The image contains a list of physical quantities and their definitions, followed by a list of Greek symbols along with their meanings. The text is formatted in a clear, readable manner, with each symbol accompanied by its description. The references section at the bottom cites various scientific sources related to the topic, including studies on solar energy and nanofluids. The paper references are listed in a numerical order, providing a comprehensive overview of the research area.
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