Performance characteristics of a residential-type direct absorption solar collector using MWCNT nanofluid

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In this study, the performance characteristics of a nanofluid-based direct absorption solar collector are investigated numerically and experimentally. The numerical model of nanofluid-based direct absorption solar collector was developed by solving radiative transfer equation combined with energy equation. The outlet temperature is analyzed by variation of internal emissivity of bottom wall, collector height, nanofluid volume fraction and flowrate. Then, a prototype of this new type of collector was built with applicability for domestic solar heating systems. As working fluid, different volume fractions of carboxyl functionalized multi wall carbon nanotubes in water and ethylene glycol mixture (70%:30% in volume) were prepared and their thermo-optical properties were presented. The procedure of EN 12975-2 standard was used for testing the thermal performance of the collector. The tests were performed in different flowrates from 54 to 90 l/h (0.015–0.025 kg/s) and two different internal surfaces (black and reflective) of bottom wall. By comparison of calculated and measured collector efficiencies for different volume fractions, it was shown that the numerical model was accurate within ±5% of the experimental results. The collector efficiency is increased by increasing nanofluid volume fraction and flowrates. The nanofluids improve the collector efficiency by 10–29% than the base fluid. The results of the study confirm that this new kind of collector can be best utilized in solar water heating applications.

1. Introduction

Solar water heating systems, as one of the renewable energy technologies used mostly in residential buildings, can reduce the use of fossil fuels as well as associated environmental problems. Scientists and engineers have been constantly made an effort to increase performance of solar collectors as the main component of any solar system [1–4]. Some studies have led to introduce Direct Absorption Solar Collector (DASC) [5,6]. In this type of solar collector, the working fluid absorbs the solar radiation directly and converts the energy to heat; therefore, the optical properties of the working fluids turn out to be main topics which should be attended, compared with thermo-physical properties. Since the common solar fluids (water, ethylene glycol, propylene glycol, etc.) are the weak absorber [7], adding nanoparticles to the working fluid as an absorbing medium have been proposed and studied in the recent years [8–13]. Taylor et al. [8] found that over 95% of incoming sunlight can be absorbed (in a nanofluid (Graphite, Al, Cu, Ag, Au/TherminolVP-1, Water) thickness > 10 cm) with extremely low nanoparticle volume fractions (0.001 vol%). Lou et al. [10] found that the absorption of nanofluids was 5 times larger than that of base oil. Zhang et al. [11] investigated the radiative properties of the ionic liquid-based nanofluids by the experimental and theoretical methods. They showed that the absorbed energy fraction by the Ni/C nanofluid reaches up to almost 100% after the incident light only penetrate 1 cm, as the volume fraction is increased to 40 ppm. Hordi et al. [12] demonstrated that the MWCNTs are highly absorbing over the majority of the solar spectrum, allowing for close to 100% solar energy absorption, even at low concentrations and small collection volumes.

By exploring the potential of nanofluids, Tyagi et al. [14] numerically investigated a low temperature nanofluid DASC for the first time. They used aluminum nanoparticle suspensions in water as the working fluid and show the efficiency enhancement of 10% in comparison with a conventional flat plate collector. In recent years, a good number of experimental and numerical works has been done in the field of solar systems through a DASC [15–21]. Otanicar et al. [15]...
have numerically evaluated the performance of low-temperature DASC based on the work of Tyagi et al. [14]. They also reported on the experimental results on microsolar direct absorption collector based on nanofluids made from a variety of nanoparticles and demonstrate efficiency improvements of up to 5% by utilizing nanofluids as the absorption mechanism. Taylor et al. extended the application of nanofluid-based DASC to high-temperature concentrated solar power systems [16]. They built a laboratory-scale nanofluid dish receiver that measures 2 cm² by 2 cm, with a fluid height of 1 mm. Their results showed that the use of a nanofluid in the receiver can improve the efficiency by 10%. Veeraragavan et al. [17] presents an analytical model that investigated the effect of heat loss, particle loading, solar concentration and channel height on temperature profiles. The obtained temperature profiles showed that at locations downstream of the inlet, the surface temperature becomes lower than the bulk temperature which suggests the advantage of volumetric absorption. Khullar et al. [18] introduced the idea of harvesting solar radiant energy through usage of nanofluid-based concentrating parabolic solar collectors (NCPCS). They observed that the NCPCS has about 5–10% higher efficiency as compared to the conventional parabolic solar collector while maintaining the same external conditions. Most recently, Parvin et al. [19] investigated the heat transfer performance and entropy generation of forced convection through a low-temperature direct absorption solar collector numerically. The results showed that both the mean Nusselt number and entropy generation increase as the volume fraction of Cu nanoparticles and Reynolds number increase. Moradi et al. [20] developed a three-dimensional model of a DASC using a computational fluid dynamics (CFD) analysis of the flow and temperature field. They found that there is a non-uniform dependence of the collector efficiency on the nanoparticle concentration in the nanofluid because higher collector surface temperature is obtained by an increase of the nanoparticle loading beyond a limit value. Gupta et al. [21] investigated the effect of Al₂O₃–H₂O nanofluid flowrate on the efficiency of direct absorption solar collector. Using an experimental setup, they show that collector efficiency enhancement of 8.1% and 4.2% has been achieved for 1.5 and 2 pm flowrate of nanofluid, respectively.

Most of the mentioned works were in the field of high temperature, high flux nanofluid solar collectors [16–18,22,23]. To the best of authors’ knowledge, a low-temperature DASC with applicability for domestic solar heating systems has not been sufficiently investigated. In this paper, a low-temperature DASC using carbonized multi wall carbon nanotubes (MWCNT) in the mixture of water and ethylene glycol (70%:30%) as working fluid for residential application is investigated. The thermo-optical properties of the nanofluids are characterized using experimental method. A two-dimensional numerical model is developed that examines the effect of internal emissivity of bottom wall, nanofluid volume fraction, collector height, and inlet mass flowrate on the temperature distribution inside the collector. An experimental setup is designed and built for testing the thermal performance of a DASC prototype based on EN 12975-2 standard. The tests were performed in different flowrates from 54 to 90 l/h (0.015–0.025 kg/s) and two different internal surfaces (black and reflective) of bottom wall for various nanofluid volume fractions. The numerical model is validated through experiments. The experimental setup is subsequently used to determine the collector efficiency by variation of different parameters.

2. Numerical simulation
2.1. Governing equations

The schematic of a DASC that was numerically simulated in this study has been presented in Fig. 1. It contains a nanofluid flowing between two parallel walls by a variable height (H). The top wall is a glass with transmittance of about 90% and the bottom wall are assumed to be insulated. The incident solar heat flux is transmitted through the glass and absorbed volumetrically by the suspended nanoparticles. The absorbed radiation results in volumetric heat generation. Moreover, because the high surface-to-volume ratio of the particles leads to instant heat transfer to the surrounding medium [24,25], the particles and the fluid are assumed to be at the same temperature and the nanofluid is modeled as a single-phase isotropic fluid.

Based on the assumptions, the radiative transport and energy equations are simultaneously solved to investigate the performance of DASC. The energy equation for a two-dimensional steady state, incompressible and laminar flow with a radiative source term may be given as:

$$\rho_f \epsilon_f C_{pf} \frac{\partial T}{\partial t} = \frac{\partial}{\partial y} \left( \frac{k_{nf} \epsilon_f c_{pf}}{\lambda_f} \frac{\partial T}{\partial y} \right) - \frac{\partial q_r}{\partial y}$$

(1)

where $\rho_f$ and $C_{pf}$ are the nanofluid thermo-physical properties (density, specific heat and thermal conductivity, respectively) and $u(y)$ is the fully-developed velocity profile, given by:

$$u(y) = -\frac{6U_0}{H^2} (y^2 - Hy)$$

(2)

The initial and boundary conditions of Eq. (1) are:

$$x = 0, \quad 0 < y < H \Rightarrow T(0,y) = T_{in}, \quad u(0,y) = U_0$$

(3)

$$x = H, \quad y > 0 \Rightarrow q_r(H) - \frac{\partial T}{\partial y} \bigg|_{y=H} = 0$$

(4)

$$y = 0, \quad x > 0 \Rightarrow -k_{nf} \frac{\partial T}{\partial y} \bigg|_{y=0} = (1 - \tau_g - \rho_g)G_T - h(T_{amb} - T_g)$$

(5)

where $h$ is the combined convection and radiation heat transfer coefficient of the top surface. The last term on the right hand side of Eq. (1) is the divergence of the radiant flux for an absorbing—emitting medium which is computed as [20]:

$$\frac{\partial q_r}{\partial y} = 4\pi \int K_{\lambda} \left[ i_0(\lambda, y) - \frac{A_0}{4\pi} \int i_0(\lambda, y, \omega) d\omega \right] d\lambda$$

(6)

where $K_{\lambda}$ is the spectral absorption coefficient, $i_0$ is the blackbody intensity given by the Planck function. The intensity $i_0$ is obtained.
by solving the Radiative Transfer Equation (RTE) in one dimension (along the $y$-direction):

$$\frac{di_j}{dy} = -K_{ii}i_j(y) + K_{ii}i_{ib}(y) + \frac{4\pi}{\omega_i} \int i_j(y, \omega_i) \Phi_j(\omega_i, \omega_i) d\omega_i$$

(7)

where $\Phi_j$ is the scattering phase function and $K_{ii} = K_{ai} + K_{ai}$ is the spectral extinction coefficient, $K_{ai}$ and the spectral scattering coefficient, $K_{ai}$. Based on the Rayleigh scattering \cite{15}, the extinction coefficient can be given as:

$$K_{ei} = \frac{3\sigma_s Q_{ei}}{2D}$$

(8)

where $\sigma_s$ is the particle volume fraction and $Q_{ei} = Q_{ai} + Q_{ai}$ is the extinction efficiency contains the absorption efficiency, $Q_{ai}$ and the scattering efficiency, $Q_{ai}$, which are given in the Rayleigh regime by the following relation:

$$Q_{ai} = 4 \pi D^1 \left( \frac{m^2 - 1}{m^2 + 2} \right)$$

(9)

$$Q_{ai} = \frac{8 \pi D^4}{3} \left( \frac{m^2 - 1}{m^2 + 2} \right)^2$$

(10)

where $m = \sqrt{n^2 + k^2}$ is defined as the normalized refractive index of the particles. As presented in Eqs. (9) and (10), the scattering efficiency scales with $D^4$, while the absorption efficiency is proportional to $D$; therefore, the contribution of scattering to the total extinction efficiency can be generally neglected ($K_{ai} \approx 0$). Regarding above assumption, the intensity distribution within the solar collector is obtained using:

$$\frac{di_j}{dy} = -K_{ai}i_j(y) + K_{ai}i_{ib}(y)$$

(11)

where $\mu = \cos \theta$, $\theta$ is the polar angle measured from the $y$-direction. Because there is no data for refractive and absorptive indexes $(n, k)$ of carbon nanotube in the literature, we have used the experimental measurements and Beer–Lambert relation for calculation of the extinction coefficient.

The emitted radiation can be determined with the Planck’s blackbody relation given in Eq. (12):

$$i_{ib}(\lambda, T(x, y)) = \frac{2hc^2}{\lambda^5 \exp \left( \frac{hc}{\lambda \epsilon B_{\text{sub}} T} \right) - 1}$$

(12)

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

The subscript $i$ is used to represent the directional nature of the intensity, $+1$ representing the direction of the solar radiation and $-1$ in the opposite direction of the incoming solar radiation. Based on Two-Flux approximation \cite{26}, Eq. (11) can be written as:

$$\frac{1}{2} \frac{di_{i,j}}{dy} = -K_{ai}i_{-1,j} + K_{ai}i_{1,j}(T(x, y))$$

(13)

which are solved using iterative method with the boundary conditions outlined by Kumar and Tien \cite{27},

$$i_{-1,j}(H) = e_{w,j}i_{1,j}[T(H)] + \rho_{w,j}i_{-1,j}(H)$$

(15)

$$i_{1,j}(0) = S_{\text{r},g,j} + \alpha_{g,j}i_{1,j}(T(0)) + \rho_{g,j}i_{-1,j}(0)$$

(16)

where $e_{w,j}$ is the spectral wall emissivity, $\rho_{w,j}$ is the spectral wall reflectivity, $\rho_{g,j}$ is the spectral glass absorptivity, and $S_{\text{r},g,j}$ is the incident spectral radiation on the top layer of the fluid:

$$S_{\text{r},j}(\lambda, T_{\text{Solar}}) = S_{\text{r},j} \frac{2hc^2}{\lambda^5 \exp \left( \frac{hc}{\lambda \epsilon B_{\text{sub}} T} \right) - 1}$$

(17)

where the sun’s temperature is assumed to be 5800 K. $Q_i$ ($6.80 \times 10^{-5}$) is the solid angle of the sun as seen from the Earth, and $S_{\text{r},g}$ (0.73) is the attenuation constant \cite{17}.

The boundary conditions for the perfect absorber and perfect reflector at the bottom of the collector are given by Eqs. (15) and (16), respectively:

$$i_{1,j}(H) = i_{1,j}[T(H)]$$

(18)

$$i_{-1,j}(H) = i_{1,j}(H)$$

(19)

Finally, the collector efficiency ($\eta$) relates the useful energy to the total radiation incident on the collector surface ($AG_T$) by Eq. (22):

$$\eta = \frac{\dot{Q}}{AG_T} = \frac{\rho V c_p (T_{\text{out}} - T_{\text{in}})}{AG_T}$$

(20)

where $V$ is the volumetric flow rate, $\rho$ and $c_p$ is the density and heat capacity of working fluid.

2.2. Solution method

In this study, the full implicit finite difference method is used to solve the governing equations along with boundary conditions. Because of the emission term, the RTE and the energy equation are coupled; therefore, an iteratively solution method with two main steps is used. In first step, the blackbody emission term in Eq. (12) is calculated based on the inlet temperature profile. Then, Eq. (13) is solved with boundary condition of Eq. (16) for 1 step forward in $x$ direction by guessing the value of $i_{-1,j}(0)$ to obtain the value of $i_{-1,j}(H)$, by which Eq. (14) is solved with boundary condition of Eq. (15) to obtain the new value of $i_{-1,j}(0)$. If the difference of this new value with the old (guess) value is negligible, the divergence of the radiative heat flux $\frac{\dot{Q}}{AG_T}$ is calculated from Eq. (7), which is then incorporated into the energy equation; otherwise, the above procedure were repeated to reach convergence.

In second step, the energy equation is solved in the same step in $x$ direction to determine the temperature profile. If these temperatures have a little difference with the initial guess of temperature distribution solved; otherwise, the new temperatures are used to update blackbody emission term and the first and second steps were repeated to achieve convergence.
The convergence of solutions is assumed when the relative error for each variable between consecutive iterations is recorded below the convergence criterion such that the difference between the new and old values is less than $10^{-3}$. A grid independence study along the y-direction is performed until the maximum variance in the temperature profile is below 0.01 K.

3. Experimental investigation

3.1. Nano fluid preparation and thermo-optical properties

In this work, carboxyl (COOH) functionalized multi wall carbon nanotubes (MWCNT) (10–20 nm in diameter and 10–30 μm in length), provided by US Research Nanomaterials, Inc., are suspended in Water-Ethylene Glycol (W-EG) mixture (70%:30% in volume) to prepare nanofluid. In our previous study, we showed CNTs are one of the best nanomaterials for DASC because of most similarly behavior of CNTs to a black body [28]. Water was chosen because of its higher absorbance between common solar fluids [7] and widespread use in low-temperature solar thermal collectors. EG is added to water as antifreeze, commonly used in solar water heaters. The two-step method is used to prepare nanofluids. The appropriate amount of MWCNT for preparation of a particular volume fraction of nanofluid was added directly into W-EG mixture and stirred well using an ultrasonic homogenizer (Hielscher, UP400S, Inc.) for 30 min at ambient temperature. Suspensions of the MWCNTs in W-EG mixture with varying volume fractions (25 ppm (f3), 50 ppm (f2) and 100 ppm (f1)) were prepared. With this procedure the long term stability was assured to the dispersions (no settling has been detected after a month) [28].

In this study, the thermo-optical properties of the nanofluids, which are used in the numerical modeling of DASC, are determined by the experimental methods. To determine the optical properties of the nanofluids, a differential measurement technique was performed using a spectrophotometer (PerkinElmer Lambda 1050). The measurement technique is similar to the one recently described by (Karami et al. [13]).

The overall transmittance spectra of the samples with respect to the air were shown in Fig. 2(a). They represent the spectral transmittance of the whole system built by NPs and base fluid. It is evident that f-CNTs considerably reduces the sample transmittance with respect to the pure fluid and enhance the amount of captured light. To better characterize of optical properties the samples, extinction coefficient was calculated from the spectral transmittance, according to the Beer–Lambert law [13]. The results at four different volume fractions have been plotted in Fig. 2(b) showing a general increase in absorption coefficient with increasing volume fraction.

Table 1 shows the corresponding experimentally determined thermophysical properties of the MWCNT nanofluids. The density of the nanofluids was obtained using Pycnometer method (ASTM D-1217) [29], whereas, the ASTM standard test method (E1269-05) [30] was followed to obtain the specific heat ($C_p$) using a differential scanning calorimeter (DSC) (SETARAM, DSC131).

The thermal conductivity (k) of the nanofluids was obtained using KD2 Pro thermal properties analyzer (Decagon devices, Inc.) which is based on transient hot-wire method [31].

The significant improvement in the thermal properties of a bulk fluid can be achieved by NPs [32]. The thermal conductivity enhancement of base fluids was confirmed with using CNT, which have the potential of efficiency increase of solar water heaters [33]. Fig. 3 shows the thermal conductivity of MWCNT nanofluids versus temperature for different volume fractions. It indicates that the conductivities of all the nanofluid samples increased as the volume fraction and the temperature increased, which can lead to increased heat transfer and hence, an enhancement in collector efficiency. For example, MWCNT nanofluid of 25 ppm volume fraction (f3) the thermal conductivity is increased from 3.6% at 25 °C to 21.6% at 60 °C, whereas the enhancement in the thermal conductivity of 100 ppm volume fraction (f1) nanofluids is from 10.0% to 54.4% at the same temperatures.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Volume fraction (ppm)</th>
<th>Density (kg/m$^3$)</th>
<th>Heat capacity (J/kgK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base fluid</td>
<td>0</td>
<td>1043.32</td>
<td>3674.39</td>
</tr>
<tr>
<td>f3</td>
<td>25</td>
<td>1043.33</td>
<td>3674.48</td>
</tr>
<tr>
<td>f2</td>
<td>50</td>
<td>1043.37</td>
<td>3674.75</td>
</tr>
<tr>
<td>f1</td>
<td>100</td>
<td>1043.35</td>
<td>3674.92</td>
</tr>
</tbody>
</table>

Table 1 Thermophysical properties of MWCNT nanofluid.
3.2. DASC design and test procedure

A prototype of Direct Absorption Solar Collector (DASC) was built that measures 60 x 60 cm$^2$, with a channel height of 1 cm with applicability for domestic solar heating systems. Fig. 4(a) shows the experimental collector schematic. The main body of the collector was made of aluminum. A manifold with pinholes is used to uniformly entry of working fluid into the channel from the bottom of the collector. Fig. 4(b) demonstrates the detail of working fluid entering the collector. Instead of manifold, three holes are considered at the top of the collector to exit the working fluid to avoid increasing the pressure drop. The collector glazing of the toughened glass with 4 mm thickness is selected due to prevent cracking caused by water pressure. The possible leakage of working fluid is restrained by mounting a seal gasket before installing the glazing which is tightened by means of aluminum frame. Under this frame, a seal tape is also mounted to more sealing. The whole collector is insulated within a Polyurethane block of 10 mm thickness to limit heat loss from the back and sides of the collector. The Polyurethane block was shielded from incident radiation with aluminum foil so as to not absorb any of the sunlight.

The internal surface of the collector bottom wall is reflective aluminum for all experiments with nanofluids and one experiment with the base fluid. The internal surface was also black painted to another experiment with the base fluid. All experiments with nanofluids were performed with the reflective internal surface to evaluate only nanofluid absorption ability; whereas the base fluid is tested with both black and reflective internal surfaces.

The DASC was experimentally investigated at the Building and Housing Research Center in Tehran, Iran (latitude is 35.6961° N and longitude is 51.4231° E). The schematic of the test loop and the photo of the test setup based on EN-12975-2 [34] are shown in Fig. 5. DASC is mounted by tilt angle of 35° to receive maximum solar energy (regarding Tehran latitude). An electrical pump and a flow control valve (connected to the water pipe after the electric pump) are used to maintain the flowrate through the collector stable to within 1%. An expansion tank with about 5 l capacity is used which has been insulated due to reduce heat loss. For primary temperature control, the working fluid was heated or cooled using a heat exchanger to remain inlet temperature constant.

Measuring instruments include a flowmeter which connected...
to the water pipe before the electric pump with the ±1% accuracy of the measuring span, two PT100 temperature sensors to measure fluid temperatures in the inlet and outlet of collector with the accuracy of ±0.1°C, another temperature sensor to measure the air temperature, Kipp&Zonen-CMP6 pyranometer to measure total solar radiation which its sensor is mounted coplanar, within a tolerance of ±0.05°C the plane of the collector aperture and TESTO 425 anemometer which recorded air speed by accuracy ± 0.03 m/s. A data acquisition system was used to record all measurements.

Calibration of measuring instruments was performed using calibrated references. The temperature sensors were calibrated using a calibrated thermometer to give an uncertainty less than ±0.05°C, the flowmeter using drawing off water from the system into a container and measuring the volume and time with accuracy scales. The uncertainty was about ±2%. The pyranometer and anemometer have a valid calibration certificates with uncertainty of about ±3.5% and ±2.5%, respectively.

The collector is tested for at least four fluid inlet temperatures over its operating temperature range under clear sky conditions. At least four independent data points are obtained for each fluid inlet temperature, to give a total of 16 data points. The data for each test period were averaged and applied as a single point whereas other periods were rejected. During a test, hemispherical solar irradiance, air speed, surrounding air temperature, to give a total of 16 data points. The data for each test period is available in Ref. [36]. The maximum uncertainty obtained in the present study in determining the collector efficiency, at various tests was around 4.7%.

4. Results and discussion

4.1. Comparison between experimental and simulation results

The results of the numerical model in comparison to the experimental results for f1 sample at 72 l/h, are shown in Fig. 7. The numerical model is shown to be accurate to within ±5% of the experimental results versus reduced temperature difference.

4.2. Collector outlet temperature

The effect of internal emissivity of bottom wall, collector height, mass flow rate and nanofluid volume fraction on collector outlet temperature is investigated with the numerical model. In all cases,

3.3. Efficiency calculation and error analysis

An instantaneous efficiency curve is obtained by statistical curve fitting of the experimental data, using the least squares method:

$$\eta = \eta_0 - a_1 T^* - a_2 G_T (T^*)^2$$

(21)

where $T^*$ is the reduced temperature difference and calculated as:

$$T^* = \frac{T_{in} - T_{amb}}{G_T}$$

(22)

The intersection of the line with the vertical efficiency axis equals to $\eta_0$ which is called zero-loss efficiency. At this point the temperature of the fluid entering the collector equals to the ambient temperature and collector efficiency is maximum. The slope of the line ($a_1$) indicates removed energy from the solar collector which called heat loss coefficient. The coefficient $a_2$ shows temperature dependence of the heat loss coefficient [30]. If the value deduced for $a_2$ is negative, a second-order fit shall not be used.

Error analysis for experimental results presented in this study (“steady-state” collector efficiency) has been performed using the method proposed by Abernethy et al. [35]. The detail of the method is available in Ref. [36]. The maximum uncertainty obtained in the present study in determining the collector efficiency, at various tests was around 4.7%.

Fig. 6. Collector time constant test for base fluid at 72 l/h flowrate.

Fig. 7. Comparison of numerical and experimental results for f1 sample at 72 l/h.
the initial temperature of the nanofluid and the ambient temperature were set to 35°C and 25°C, respectively. The incident radiation was assumed to be 800 W/m² and the heat transfer coefficient including both convective and radiative heat loss was assumed to 15W/m²K. With these conditions fixed, collector outlet temperature profiles are shown in Fig. 8.

The effect of the internal emissivity of the bottom wall on the collector outlet temperature with the base fluid as working fluid is indicated in Fig. 8(a). As can be seen, the higher outlet temperature is achieved by increasing the internal emissivity. When the bottom wall has the reflective internal surface ($\varepsilon = 0$), solar radiation incident on the top wall was partly absorbed by the fluid before it reached the bottom, where it got reflected back into the fluid. This reflected radiation was again absorbed partly by the fluid before being transmitted out of the domain through the semi-transparent top wall. However, when the bottom wall has the black (absorptive) internal surface ($\varepsilon = 1$), any radiation reaching there was absorbed by it. This caused the temperature of the bottom wall to rise significantly, and that of the fluid in its vicinity, as can be seen in Fig. 8(a). This resulted in a higher mean fluid temperature in the fluid layer, and hence a higher collector efficiency, which will be experimentally investigated in the next section.

The collector outlet temperature at various volume fractions for a 72 l/h flowrate and 10 mm collector height is shown in Fig. 8(b). It can be resulted from this figure that at constant flowrate, the collector outlet temperature is increased by increasing nanofluid volume fraction, resulted in the fluid absorption coefficient increase. It should be noted that the temperature increase by varying the volume fraction from zero (base fluid) to 25 ppm ($f_3$) is more than that by varying the volume fraction from 25 ppm ($f_3$) to 50 ppm ($f_2$). This shows that temperature increase has an asymptotic trend with increasing of volume fraction. For low volume fraction, most of the radiation incident on the top wall penetrated the fluid layer and reach the bottom wall. This leads to more uniform temperature profile, which limits the amount of heat loss at the boundaries.

For high volume fraction, although the solar energy absorption is increased, but fluid adjacent to the top wall absorbed most of the radiation incident on it, allowing little radiation to penetrate the fluid layer and reach the bottom wall. This resulted in a high temperature region near the top wall, with the attendant heat losses and reduction in temperature increase. The trade-off between the two effects (higher absorption and higher heat loss at higher volume fraction) described above accounts for the trend seen in Fig. 8(b).

Fig. 8. Effect of various parameters on the collector outlet temperature (a) internal emissivity of bottom wall (b) nanofluid volume fraction (c) collector height (d) inlet flowrate.
The effect of collector height on the collector outlet temperature is clarified in Fig. 8(c) for a 72 l/h flowrate and 100 ppm nanofluid volume fraction. It can be observed from this figure that the average outlet temperature is increased from 36.2°C at 5 mm height to 36.8°C at 20 mm height. Based on the Lambert’s law, the absorbance is directly proportional to the thickness (i.e., the path length) of the sample [33]. For small values of height, the radiation incident onto the top wall passed the small path length; therefore, the less absorbance occurs. For large collector heights, more radiation is absorbed due to the larger path length and thus, the more temperature is achieved. However, higher temperature is observed at the topmost layers for large values of height and more heat is lost to the ambient. This is evident from the temperature near the bottom wall in Fig. 8(c). For this reason, increasing the collector height had no added advantage beyond a point in preventing fluid heating near the top wall. Hence the collector outlet temperature was independent of collector height for high values of height.

The effect of mass flowrate on the collector outlet temperature is shown in Fig. 8(d) for 10 mm collector height and 100 ppm nanofluid volume fraction. It is found that the outlet temperature decreased with flowrate. This can be described as follow. At low flowrates, the time delay between the entry and exit of working fluid into and out of the collector, i.e. the fluid residence time, is high, allowing for the fluid temperature to rise more.

4.3. Collector efficiency

In this section, the effect of internal emissivity of bottom wall, mass flowrate and nanofluid volume fraction on the collector efficiency is investigated using the experimental setup. The tests have performed around solar noon when the hemispherical solar irradiance is greater than 700 W/m², diffuse solar irradiance is less than 30% and the average value of air speed is 2–4 m/s. Each test was repeated in several days and the best experimental data has been chosen. The experimental results are presented in the form of graphs that describe the collector efficiency against the reduced temperature difference \((\frac{T_{in} - T_{amb}}{G_{r}})\).

The effect of the internal emissivity of the bottom wall on the collector efficiency of the collector with the base fluid as working fluid at 72 l/h is indicated in Fig. 9. As can be seen, the results confirm the numerical result; i.e., the collector efficiency is higher using absorptive internal surface than to the reflective one.

The collector efficiency at various volume fractions for a 72 l/h flowrate is shown in Fig. 10. It can be resulted from this figure that at constant flowrate, the collector efficiency was increased by increasing nanofluid volume fraction, which causes thermal conductivity and absorption coefficient increase (Section 3.1). Using the numerical model, the portion of nanofluid absorption coefficient and thermal conductivity increase in the improvement of collector efficiency can be distinguished. For this purpose, the collector efficiency was reported with the absorption coefficient (from Fig. 2(b)) and the thermal conductivity of the base fluid (0.47 W/mK from Fig. 3) and again, with the absorption coefficient of the base fluid (from Fig. 2(b)) and the thermal conductivity of the f1 sample (0.56 W/mK from Fig. 3). It was found that the efficiency increase is less than 4% by the thermal conductivity increase, while the efficiency increase of 26% was achieved by the volume fraction increase from 0 (base fluid) to 100 ppm (f1 sample), based on the results shown in Fig. 8. Therefore, about 22% of this increase arises from the high absorption coefficient of f1 sample. Since the volume fraction of nanofluids used in DASC are extremely low, the thermal conductivity plays an insignificant role in DASC efficiency increase.

It should be noted that the efficiency increased considerably by the addition of small amounts of nanoparticles (25 ppm (f3)) than to the base fluid, but after that efficiency improvement is marginally by increasing nanofluid volume fraction; so that, the zero-loss efficiency enhancement with volume fraction variation from 0 (base fluid) to 25 ppm (13%) is larger than the enhancement with volume fraction variation from 50 ppm to 100 ppm (6%).

From Fig. 10, it can be concluded that the slope of the efficiency curve decreased with volume fraction variation from 0 (base fluid) to 25 ppm; however, by further increasing the volume fraction, the slope gets a reversed trend. As aforementioned, the slope of the efficiency curve shows the overall heat loss coefficient (including convective and radiative heat transfer and outgoing reflected radiation). When the base fluid is used, the outlet temperature, and therefore, the convective and radiative heat loss to the ambient are low; but the outgoing reflected radiation to the ambient is high because the bottom wall is reflective. When the nanofluid with low volume fraction (25 ppm) is used, in spite of the outlet temperature and therefore, the convective and radiative heat loss are increased, but the outgoing reflected radiation to the ambient is lower.

![Fig. 9. Effect of internal emissivity of bottom wall on collector efficiency at 72 l/h mass flowrate.](image)

![Fig. 10. Effect of nanofluid volume fraction on collector efficiency at 72 l/h flowrate.](image)
deduced for \( a_2 \) is negative, a first-order fit is used [30]. As can be seen, \( \eta_0 \) value of the collector for 90 l/h (0.025 kg/s) and 100 ppm nanofluid (f1) is highest (89.3%), and \( a_1 \) value in this flowrate and volume fraction is lowest (19.21 W/m²K), whereas the lowest \( \eta_0 \) (50.2%) and the highest \( a_1 \) (20.18 W/m²K) are obtained for the base fluid with reflective internal surface at 54 l/h (0.015 kg/s) flowrate.

From the current study the calculated collector efficiency (\( \eta_f \)) are correlated with volumetric flowrate (\( V \)) and volume fraction (\( f_v \)) with \( 0 \leq f_v \leq 100 \text{ppm} \) and 54 l/h \( \leq V \leq 90 \text{ l/h} \), through the DASC. This correlation can be written as:

\[
\eta_{f-CNT} = (0.31V + 35.5)(f_v + 1)^{0.075} - (-0.01V + 20.9)(f_v + 1)^{0.015} \left( \frac{T_{in} - T_{amb}}{G_{f}} \right) \]  

(23)

where the confidence coefficient are \( R^2 \approx 97\% \) for both \( \eta_0 \) and \( a_1 \).

5. Conclusion

This study investigated the performance characteristics of a nanofluid-based DACS with nanofluids. A numerical model was developed by combining the radiative heat transfer equation with energy equation to predict the outlet temperature profiles, varying different parameters. Functionalized multi wall carbon nanotubes were applied in nanofluids, whose properties were reported. These results are used in the numerical model. A prototype of MWNT nanofluid-based direct absorption solar collector (DASC) was built with applicability for domestic solar heating systems. The effect of internal emissivity of bottom wall, flowrate and MWNT nanoparticles volume fraction on the efficiency of the collector is studied. The collector efficiency increased by increasing nanofluid volume fraction and flowrate; however, this increase has asymptotic trend. The results show that zero-loss (maximum) efficiency of the collector for 90 l/h and nanofluid with 100 ppm volume fraction is highest; so that, the collector efficiency is about 29% more than that of using the base fluid as working fluid at similar flowrate. Such increase in efficiency will potentially enable more effective use of solar heating systems for various purposes, especially in applications where low temperatures (lower than 70 °C) are used such as solar combisystems, providing domestic hot water and space heating by means of floor heating.

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Nomenclature

\( a_1 \) heat loss coefficient W m\(^{-2}\) K\(^{-1}\)  
\( a_2 \) temperature dependence of heat loss coefficient W m\(^{-2}\) K\(^{-2}\)  
\( A \) area m\(^2\)  
\( c \) light velocity ms\(^{-1}\)  
\( c_P \) specific heat J kg\(^{-1}\) K\(^{-1}\)  
\( D \) particle diameter m  
\( f_v \) volume fraction  
\( G \) incident solar radiation W m\(^{-2}\)  
\( h \) Planck constant Js  
\( h \) heat transfer coefficient W m\(^{-2}\) K\(^{-1}\)  
\( H \) height m  
\( i \) spectral radiation intensity W m\(^{-2}\) \(\mu\)m\(^{-1}\)  
\( k \) thermal conductivity W m\(^{-1}\) K\(^{-1}\)  
\( k \) absorptive index  
\( K \) extinction coefficient m\(^{-1}\)  
\( K_B \) Boltzmann’s constant JK\(^{-1}\)  
\( m \) mass flow rate kg s\(^{-1}\)  
\( m \) normalized refractive index  
\( n \) refractive index  
\( q_r \) radiative heat flux W m\(^{-2}\)  
\( Q \) Extinction efficiency  
\( R^2 \) confidence coefficient  
\( S_i \) spectral solar radiation W m\(^{-2}\) \(\mu\)m\(^{-1}\)  
\( S_{att} \) attenuation constant  
\( T \) temperature K  
\( T^* \) reduced temperature difference K/Wm\(^{-2}\)  
\( \dot{V} \) volumetric flow rate lh\(^{-1}\)  
\( u \) velocity ms\(^{-1}\)  
\( U_0 \) inlet velocity ms\(^{-1}\)  
\( \chi, \gamma \) coordinates m

Greek symbols

\( \alpha \) absorptivity  
\( \rho \) density kgm\(^{-3}\)  
\( \rho \) reflectivity  
\( \varepsilon \) emissivity  
\( \tau \) transmissivity  
\( \omega \) Solid angle steradian  
\( \lambda \) wavelength m  
\( \eta \) efficiency  
\( \mu \) the quantity cos\(\theta\)  
\( \Omega_s \) sun solid angle  
\( \Phi \) scattering phase function

Subscripts

abs absorbed  
amb ambient  
b black body  
e extinction  
g glass  
indirectional  
in inlet  
out outlet  
nf nanofluid  
r radiative  
s scattering  
\( \lambda \) spectral

References