

Silicone oil envelope for enhancing the performance of nanofluid-based direct absorption solar collectors

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ABSTRACT

Nanofluids inherently have high emissivity in the mid-infrared region making them unsuitable for satisfying the conditions of solar selectivity required for direct absorbers. In this study, a layer of silicone oil is located above nanofluid comprising of graphite nanoparticles and deionized water. Silicone oil layer is shown to act as a barrier against the infrared emissions from the nanofluid. High transparency of silicone oil in the visible solar spectrum and high absorptivity in the mid-infrared wavelength range made it an excellent candidate for this study. Solar selectivity was achieved by using two different liquid layers (nanofluid and silicone oil) in direct thermal contact. Silicone oil layer on the top of the nanofluid resulted in an approximately 17% higher temperature rise in the nanofluid.

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1. Introduction

Solar thermal collectors have been historically developed, to harness incident solar energy (80,000 TW globally). In the conventional collectors, solar radiation is absorbed by an absorber plate (a selectively coated metallic plate), converted into heat and transferred by conduction and convection heat transfer mechanisms to working fluid [1]. However, at high flux conditions the conversion efficiency of such surface absorption systems reduces due to an enhanced radiative loss resulting from a high temperature difference between the absorber surface and the working fluid [2]. This situation can be avoided by absorbing solar radiation directly by the working fluid itself. In this context, systems using nanoparticle-laden working fluid, famously known as directly absorbing solar collectors (DASCs), have been investigated and shown to have an improved performance over commercially

available surface-based solar collectors [3–6,10–12]. Different configurations such as gas-particle suspension [7,8], liquid films [9] have also been proposed. Direct absorption of solar radiation has been reported to be a function of parameters such as the concentration level of the nanoparticles in the base fluid and their material and shape [10–13]. Literature shows that most of the research focused on the efficiency enhancement of the solar collector and the efficiency of the collector can be enhanced more by making them solar selective [14]. Two conditions are required to make the DASC as solar selective, which are as follow: (a) high absorptivity in the short wavelength ($\lambda < 2.5 \mu\text{m}$) and (b) low emissivity at high wavelengths (typically in the mid infrared region, $\lambda = 2.5\text{--}10 \mu\text{m}$) [12,14–16]. Restricting the emissive losses results into a significant improvement in the performance of the solar collector [13,17,18]. Several applications of nanofluid-based solar thermal systems have been reviewed in the recent years, and a summary of the review papers related to this field are presented in Table 1 [14].

The present experimental study investigates the use of silicone oil (Sigma Aldrich, viscosity 50 cST at 25 °C) layer above the amorphous carbon nanoparticles (Sigma Aldrich, < 50 nm particle size, granular) laden water to reduce the radiative loss. Amorphous

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Table 1
Summary of review papers related to optical properties and thermal performances of the direct absorption based solar collector (table reprinted with permission from Bhalla and Tyagi [14]).

Sr. No.	Authors	Year	Applications Solar Collectors (SC) or Optical Properties (OP)	Summary
1.	Mahian et al. [19]	2013	SC: 1. Solar collectors and solar water heaters 2. Photovoltaic/thermal (PV/T) collector systems 3. Solar ponds 4. Solar cells 5. Thermal energy storage 6. Solar stills	<ul style="list-style-type: none"> • Various volume fractions should be tested to find an optimum volume fraction of the nanoparticles. • Collector efficiencies should be tested with different nanoparticle sizes.
2.	Phelan et al. [20]	2013	SC: Nanoparticles-laden fluid-based 1. Low-temperature systems 2. Medium-temperature systems 3. High-temperature systems	<ul style="list-style-type: none"> • Direct absorption solar collectors have good potential in the harnessing of the solar energy due to high solar energy absorption capability.
3.	Hossain et al. [21]	2014	OP: 1. Rayleigh scattering approach 2. Maxwell-Garnett effective medium approach 3. Lambert-Beer approach 4. Mie and Gans approach 5. TL & I-scan method (Based on Fresnel approximation) 6. Discrete dipole approximation (DDA approach)	<ul style="list-style-type: none"> • The optical properties of metallic and non-metallic nanoparticles-laden fluid shows improved attenuation of the light.
4.	Suman et al. [22]	2015	SC: Solar thermal collectors	<ul style="list-style-type: none"> • The performance of the solar collector can be enhanced by using extended surface, ribs, corrugations, and with the addition of nanoparticles in the working fluid.
5.	Kasaeian et al. [23]	2015	SC: 1. Concentrating type 2. Non-concentrating type 3. Evacuated solar collector 4. Photovoltaic thermal system 5. Thermal energy storage 6. Solar thermoelectric devices 7. Solar cells	<ul style="list-style-type: none"> • The reduction in the agglomeration leads to high thermal efficiency of the solar collector.
6.	Leong et al. [24]	2015	Both SC and OP: 1. Rayleigh Scattering Approach 2. Maxwell-Garnett effective medium approach 3. Lambert-Beer approach & Solar thermal collectors	<ul style="list-style-type: none"> • Various challenges like stability of nanoparticles, effective cost and use of direct absorption based solar collector for heating are still need to address.
7.	Verma and Tiwari [25]	2015	SC: Solar collectors	<ul style="list-style-type: none"> • The thermal efficiency of photovoltaic/thermal (PV/T) can be enhanced with the use of nanoparticles.
8.	Ahmed Kadhim Hussein [26]	2016	SC: 1. Flat plate solar collector 2. Direct absorption solar collector 3. Parabolic trough solar collector 4. Wavy solar collector.	<ul style="list-style-type: none"> • More efforts are needed on the reliability of nanoparticles from environmental and economic point of view. • Future research should be in the manufacturing of non-toxic and low cost nanoparticles.
9.	Muhammad et al. [27]	2016	SC: Nanoparticles-laden fluid-based 1. Flat plate solar collector 2. Evacuated tube solar collector 3. Direct absorption solar collector	<ul style="list-style-type: none"> • Challenges like agglomeration of the nanoparticles, instability of nanoparticles and increase of viscosity of the nanoparticles need to address.
10.	Ahmad et al. [28]	2017	OP: Optical properties of nanoparticles-laden fluid 1. Metallic 2. Non-metallic 3. CNTs 4. Graphene and Graphite	<ul style="list-style-type: none"> • Absorption, scattering and extinction coefficients are dependent of volume fraction and the particle size.

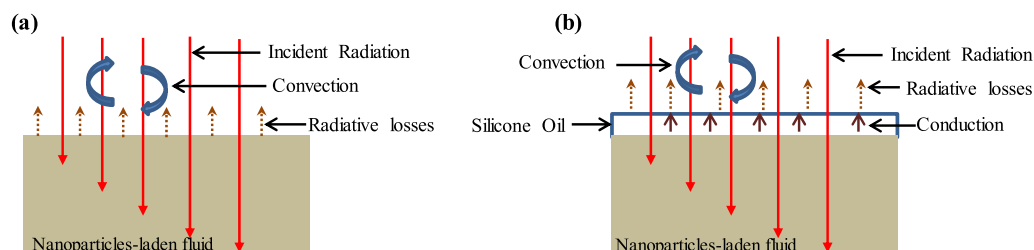


Fig. 1. Schematic of energy absorption and losses to the environment for (a) NASW/OSO and (b) NASWSO (figure reprinted with permission from Bhalla and Tyagi [14]).

carbon-based nanofluid has been used for the present experiments because previous studies suggest that graphite (carbon) nanoparticles-based fluid has higher absorptivity in the visible spectrum, i.e. $0.3\text{--}0.7\text{ }\mu\text{m}$ [14,29–31]. Selection criterion for the silicone oil layer is that, it is 100% transparent in the visible solar spectrum and high absorption in the mid-infrared wavelength range. Thus, the conditions of solar selectivity can be met through a two layer fluid system comprising silicone oil layer and nanofluid layer placed in direct thermal contact. The experimental study has been divided into two cases: (a) nanofluid based absorption system without silicone oil (NASW/OSO) and (b) nanofluid based absorption system with silicone oil (NASWSO). In both the cases, samples have been irradiated from the top to understand and evaluate the thermo-physical performance under similar operating conditions.

2. Theory

In a directly absorbing nanofluid layer radiative and convective losses occur from the top surface of the nanofluid; see Fig. 1(a). Moreover, if the temperature of the fluid gets significantly high due to prolonged exposure to solar irradiances, evaporative losses can also become significant (in some cases more than 40% of the losses) [32,33].

A thin layer of silicone oil placed on the top surface of the nanofluid is shown in Fig. 1(b). In this stratified fluid case, infrared radiation originating from heated nanofluid will get absorbed by the silicone oil layer.

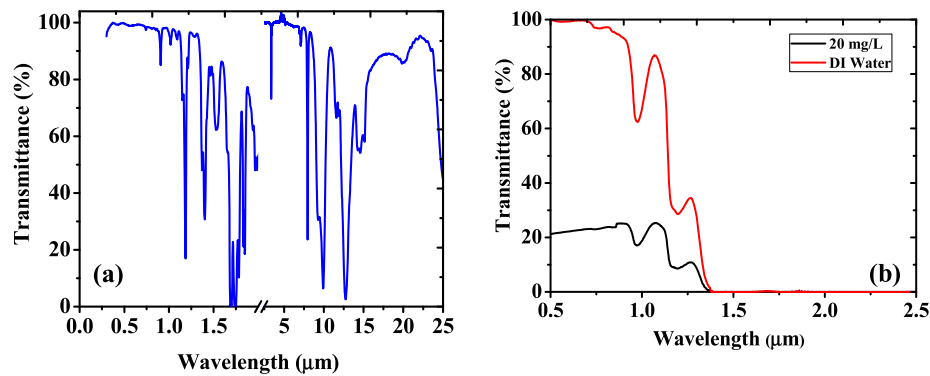


Fig. 2. (a) Transmittance spectrum of (a) silicone oil in short and long wavelength range, and (b) (b) pure deionized water and amorphous carbon based nanofluid (20 mg/L).

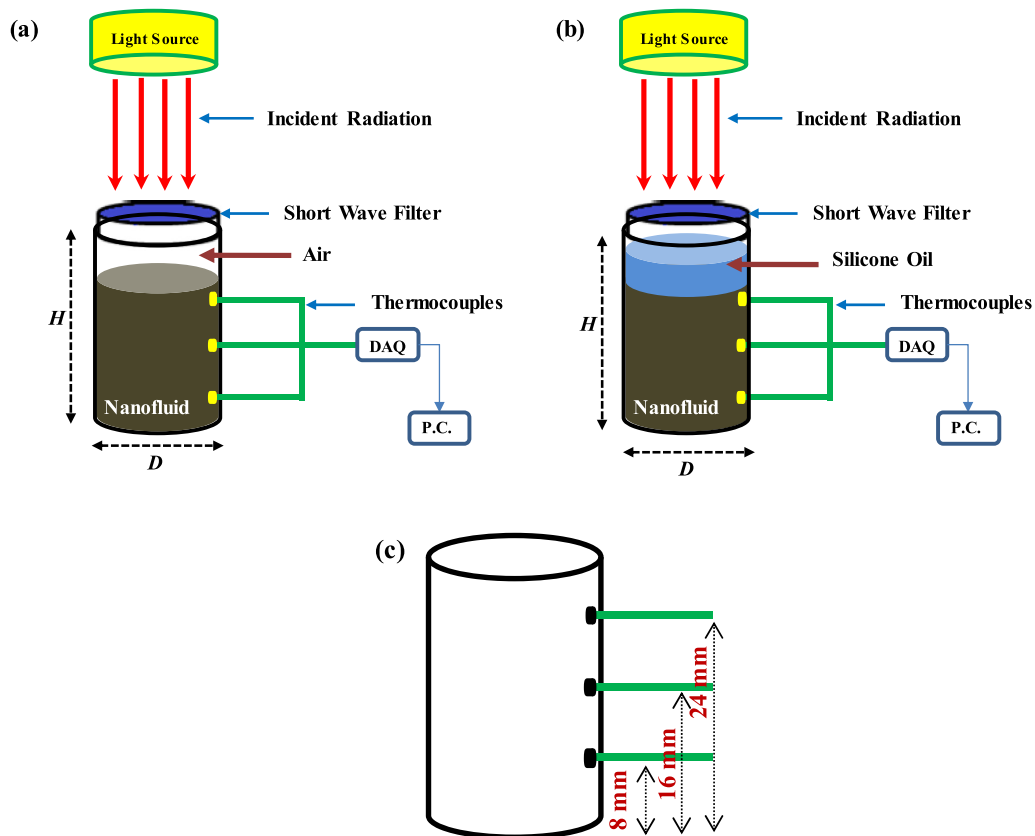


Fig. 3. Schematic of experimental setup consisting light source (Halogen Lamp), thermocouples, Data Acquisition System (DAQ), short wave filter for (a) NASW/OSO, (b) NASWSO and (c) thermocouple locations.

3. Materials and methods

3.1. Preparation of nanofluid

Different mass fractions of the nanofluid has been prepared by following the steps mentioned below [15,25]:

- Different mass fractions of the nanoparticles (viz. 20, 40, 60 and 80 mg/l) added to the de-ionized water
- Surfactant (Sodium dodecylsulfate) added in the mixture of nanoparticles and de-ionized water
- The mixture of nanoparticles and de-ionized water sonicated with probe-type ultra sonicator for 40 min
- Nanofluid cooled down to room temperature (from 38 °C to 33 °C) to have same initial temperature at the beginning of each test.

The TEM image for the nanoparticles, along with detailed study of the nanoparticle size distribution, and the stability of the nanofluid suspension, is published in our priori publication [34].

3.2. Optical properties of nanofluid and silicone oil

Transmittance of the nanofluid and silicone oil over a wavelength range of 0.3 μm –2.5 μm was measured with UV–Vis spectrophotometer (Perkin Elmer Lambda 950) keeping fluid layer thickness of 10 mm. Long wavelength (2.5 μm –25 μm) transmittance of the fluids was measured using Nicolet iS50 FT-IR spectrophotometer which works on attenuated total reflection (ATR) technique. In this technique the depth of penetration of the IR beam is very small (1 μm –15 μm) and from this small depth of penetration, spectral transmittance of highly absorbing liquids can be determined [34]. The optical signature of silicone oil for the short and long wavelength region has been shown in Fig. 2(a) and that of the nanofluid and de-ionized water in Fig. 2(b). Fig. 2(a) shows that the silicone oil has nearly 100% transmittance in the nearly full visible region (0.3–0.7 μm) whereas at the longer wavelength (1–2 μm and 5–15 μm), discrete absorption peaks can be seen. The solar spectrum intensity lies within the range of 0.2 μm –3 μm [35]. Given that almost 90% of the solar irradiation is incident in the spectral range of 0.2 μm –1.5 μm , it is estimated that not more than 5–10% of the solar irradiation would be directly absorbed by a thin layer of silicone oil. Clearly, it can be used for solar selectivity applications like the one proposed here. Furthermore, Fig. 2(b) shows that the de-ionized water has 100% transmittance in the visible region of the solar spectrum and with the addition of amorphous carbon nanoparticles in water (20 mg/L) the transmittance decreases indicating a rise in the radiation absorption in this range.

3.3. Evaluation of photo thermal conversion

For the testing of stratified fluid a table-top experimental set up (Fig. 3) similar to that used in previously published papers by our group [12,36]. Fig. 3(a) shows the experimental set up without silicone oil and Fig. 3(b) with silicone oil. A halogen lamp (Philips, colour temperature 3400 K) was used to illuminate the fluid layers. The irradiation produced by the halogen lamp is not as close to solar irradiation, as produced by a solar simulator, however there is large overlap between the wavelength of the two. Radiative flux from the halogen lamp was measured with an optical power meter and a thermopile detector (Newport optical, 1918-R and 818P) by locating short wave filter (SWF) on the top of thermopile detector [12,36]. The uncertainties involved in the measurements using optical power meter and a thermopile detector were 5% and

10% respectively. This SWF arrangement only allowed the heating of the fluid by absorption of the visible spectrum. Glass receiver tube was used. To measure the spatial temperature rise of nanofluid in the receiver, three K-type thermocouples were located at three different heights, 8 mm, 16 mm and 24 mm, measured from the base, as shown in Fig. 3(c), and another thermocouple was used to measure the ambient temperature. Thermocouples were placed near to the wall of the receiver tube in order to avoid any direct irradiation incident on them. Before running each set of experiments the thermocouples were calibrated with a water bath. Based on repeated measurements the uncertainty in the temperature measurement of thermocouples was found to be less than 0.5 °C.

3.4. Optimum amount of silicone oil

Freshly prepared nanofluid, at room temperature, with and without silicone oil layer (the silicone oil layer thickness was approx. 3 mm) was illuminated for 240 s through a short wave filter placed on the top of the receiver and the temperature rise measured.

Two quantities of silicone oil, 1 ml and 1.5 ml, were investigated in conjunction with two concentration levels of nanoparticles, 20 mg/L and 40 mg/L. The results are shown in Fig. 4(a)–(b) respectively. In both these figures it is observed that the temperature increased with time. Fig. 4(a) shows that the temperature rise was minimum for the case when no silicone oil was used, whilst the other two cases recorded a higher temperature rise by 3 °C. Interestingly there was almost no difference in the temperature for the

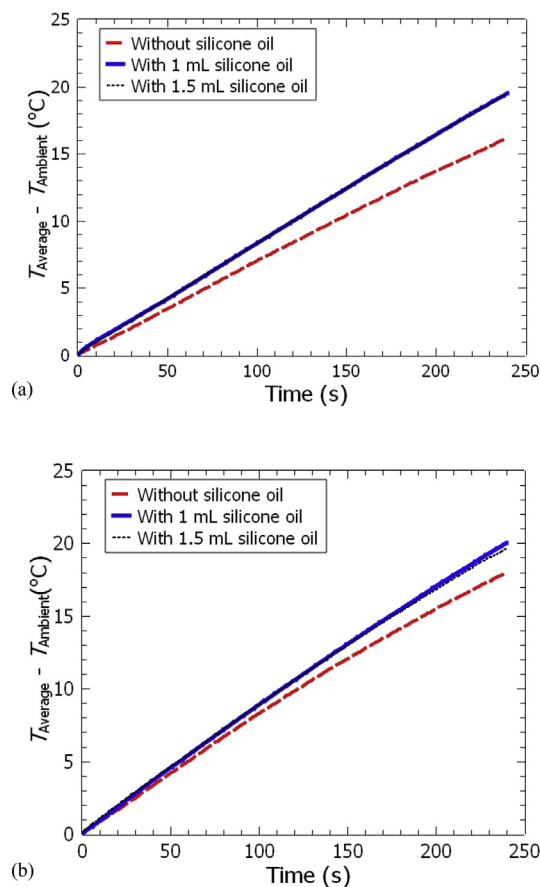


Fig. 4. Average temperature rise of nanofluid-based absorption system for two different amounts of silicone oil (1 ml, 1.5 ml), for nanoparticle concentrations of (a) 20 mg/L and (b) 40 mg/L.

latter two cases. This can be also seen in Fig. 4(b).

From these observations, it was concluded that 1 ml is a sufficient amount of silicone oil to be used in the current setup, since any further rise in the amount of silicone oil above it (1.5 ml) had no effect on nanofluid temperature rise. Therefore, for all the subsequent experiments silicone oil amount was fixed at 1 ml.

4. Results and discussion

Temperature rise for four different graphite nanoparticle concentrations, 20 mg/L, 40 mg/L, 60 mg/L, and 80 mg/L, have been shown in Fig. 5. Difference between the arithmetic average of the temperatures measured by three thermocouples and the room temperature have been plotted. The arithmetic average temperature was calculated by using equation (1) and it gives an average temperature (T_{average}).

$$T_{\text{average}} = \frac{\sum T}{N} \quad (1)$$

where T is the temperature measured and N is the number of thermocouples.

As mentioned earlier, all four samples (20 mg/L, 40 mg/L, 60 mg/L, and 80 mg/L) were irradiated for the same duration, 240 s, under identical conditions – room temperature and sample mass.

Fig. 5(a) shows the rise in temperature for 20 mg/L concentration level nanofluid with and without silicone oil. Both the cases recorded an increase in temperature-rise with time; approximately 16 °C without silicone oil and a much higher rise of about 19.5 °C with silicone oil. Benefit of using silicone oil is evident.

A similar trend was observed in other three graphite nanoparticle concentrations as well, see Fig. 5(b), (c) and (d) respectively for 40 mg/L, 60 mg/L, and 80 mg/L concentration levels. Fig. 6 summarises the temperature rise achieved by nanofluid using four nanoparticle concentration levels, 20 mg/L, 40 mg/L, 60 mg/L and 80 mg/L s. This figure clearly shows that nanofluid with 60 mg/L concentration in conjunction with 1 ml of silicone oil returned the highest rise in temperature. The lowest temperature rise was recorded for nanofluid with graphite nanoparticle concentration of 80 mg/L without silicone oil.

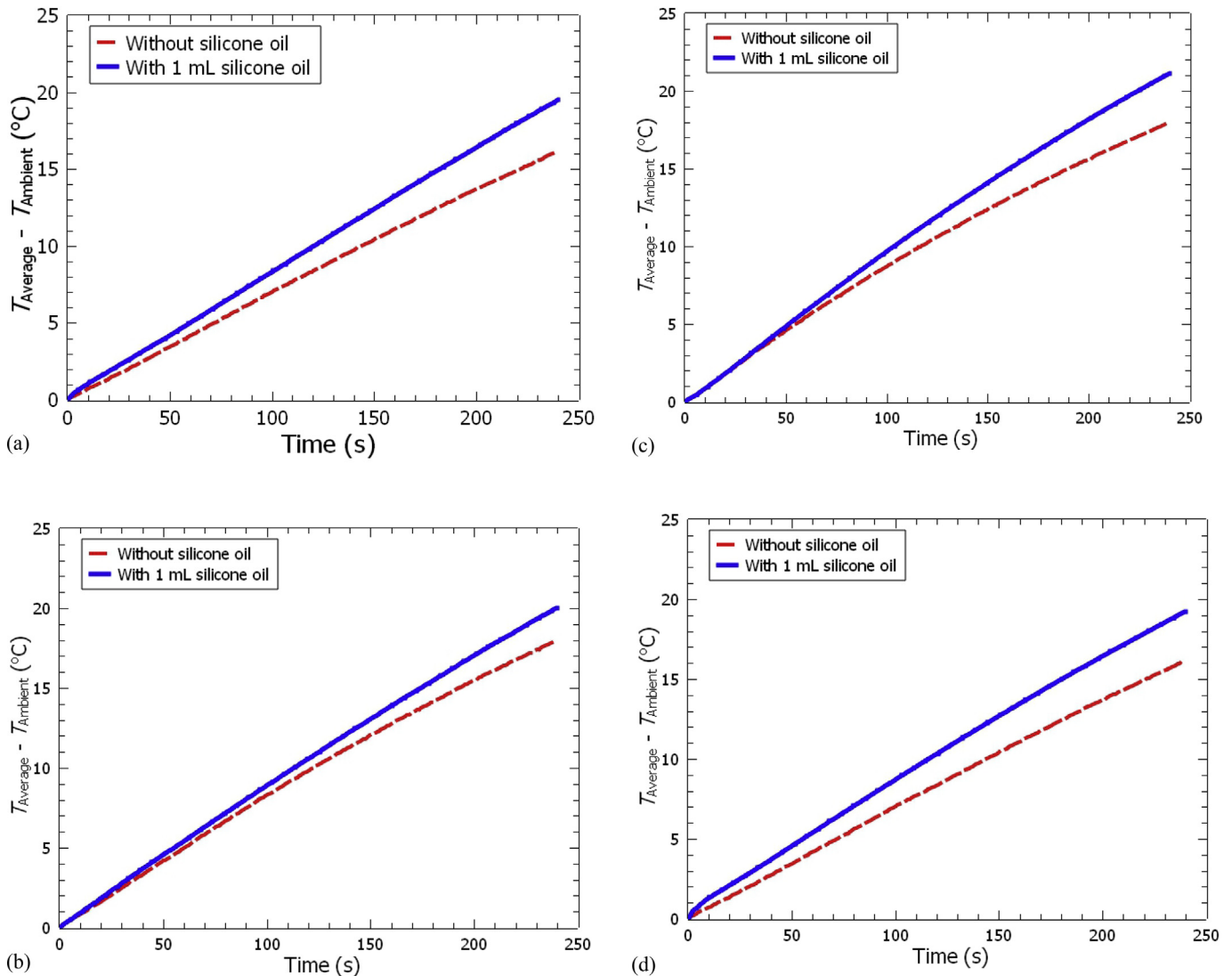


Fig. 5. Average temperature rise of nanofluid-based absorption system (for both cases - with silicone oil and without silicone oil), at the nanoparticle concentrations of (a) 20 mg/L, (b) 40 mg/L, (c) 60 mg/L, and (d) 80 mg/L.

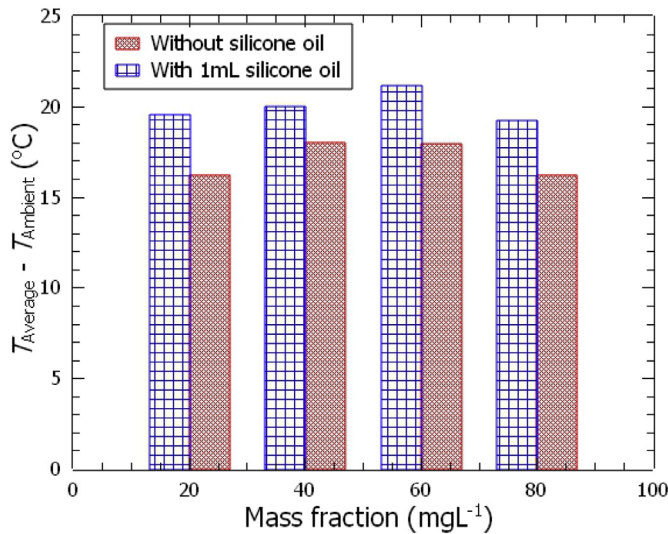


Fig. 6. Temperature rise measured for four nanoparticle concentration levels, 20 mg/L, 40 mg/L, 60 mg/L, 80 mg/L.

4.1. Applicability of silicone oil layer in solar collectors

As mentioned in the previous sections, in our experiments setup, silicone oil is present on top of the absorbing medium (graphite particle-laden nanofluid). In these experiments, both the fluids (silicone oil and nanofluid) are stagnant, since the scope of these experiments was to validate the use of silicone oil envelope for enhancing the temperature of the fluid. In an actual solar collector the working fluid (nanofluid) would be flowing within the collector (while the silicone layer would be stationary), therefore certainty differences in design and operation may be expected. However, the overall concept would remain the same. To explore such a scenario, a numerical simulation has been carried out. The description of the problem considered for numerical simulation is as follows. A flat plate-type solar collector is modelled, as shown in Fig. 7. This solar collector has an opaque bottom surface (also adiabatic), which prevents any heat transfer from the solar collector to the ambient. The nanoparticle-laden fluid flows through the collector horizontally, as shown in Fig. 7. It is covered by a thin glass

cover, having very high transmissivity ($\tau = 0.9$). On top of this glass cover, a stationary layer of silicone oil is present. Lastly, the silicone oil is covered by a glass cover, which is itself exposed to the surroundings. Therefore in this configuration, the solar irradiation is considered to be incident normally on the top glass cover. The irradiation passes through the 2 glass covers, and the silicone oil, and is then absorbed by the nanofluid flowing beneath it. Once the system gets heated and attains steady state, certain thermal losses will take place from the system. For example, the top glass cover will lose heat to the ambient due to convective losses. And moreover there will be emission losses as well. The objective of performing this numerical simulation are two-fold.

- Firstly, to compare the results between the “with silicone oil” and ‘without silicone oil’ cases, and
- secondly to compare the results with a benchmark study (Ref [37]), which was an experimental study on conventional flat-plate type solar collectors.

In order to perform a fairly accomplish objective (b), the ambient conditions in our model have been considered exactly similar to the ones in Ref. [37]. These conditions along with the geometrical parameters, as well as the fluid and nanoparticle details are provided as follows. The length of the collector (L), height of the collector (H), the height of the silicone oil layer (H_{SO}), and the velocity of the nanofluid (U) are taken as 1 m, 0.1 m, 3 mm, 1 m/s respectively. The nanofluid consist of water as the fluid, and graphite nanoparticles ($D = 50$ nm; and mass fraction = 60 mg/L). The fluid inlet temperature was taken as 35 °C. The ambient temperature was taken as 25 °C, the convective loss coefficient from the top cover was taken as 6.43 W/m²K, and the normal incident solar irradiation was taken as 1000 W/m² (these values were taken same as Ref [37] in order to obtain a fair comparison). Based on the aforementioned parameters, a numerical model was prepared and solved numerically using Finite Difference Method, in SCILAB. Essentially it involved the solving of 2D steady state heat transfer equation, and 1D RTE (radiative Transport Equation). The details of the methods are similar to the one described in our previous work [3], and therefore those mathematical relations have not been presented in detail here. The main parameter of interest in our simulation was the overall collector efficiency (η), which is plotted in Fig. 8, and whose expression is given by Eq. (2) below [3]:

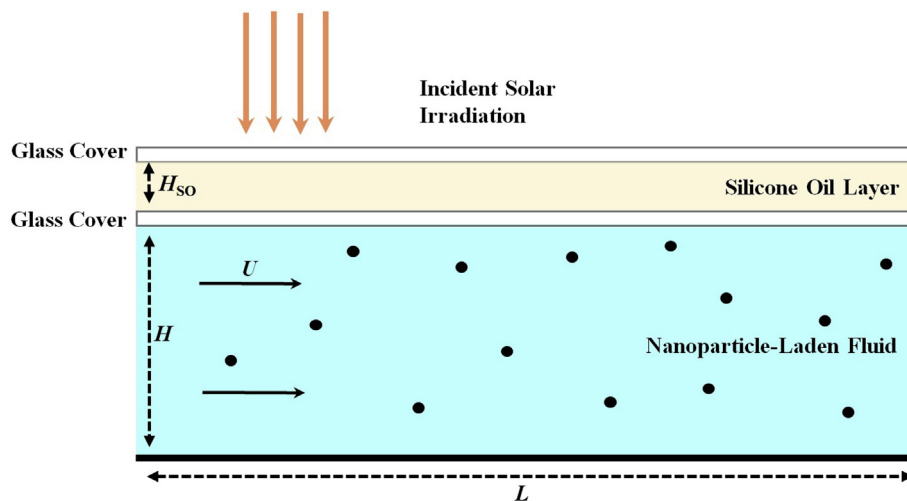


Fig. 7. Schematic of the solar collector operating on nanoparticle-laden fluid, along with a layer of silicone oil in the top.

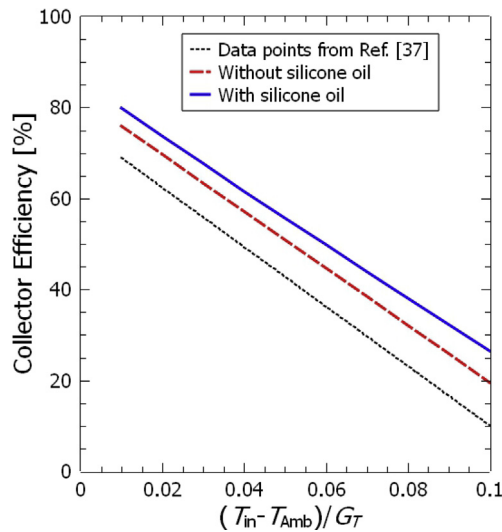


Fig. 8. Collector efficiency as a function of the collector inlet temperature (at constant values of ambient temperature (T_{Amb}), and the incident solar flux (G_T)).

$$\eta = \frac{mc_p(\bar{T}_{out} - \bar{T}_{in})}{AG_T} \quad (2)$$

where m is the nanofluid mass flow rate, c_p is the specific heat of the nanofluid, T_{out} and T_{in} are respective mean outlet and inlet temperatures of the nanofluid, A is the top glass-cover cross-sectional area, and G_T is the incident solar flux.

Fig. 8 shows the results of the numerical simulation. This figure shows 3 curves – the first curve shows the data from Ref. [37], which was an experimental study conducted on flat plate conventional solar collectors; the second curve shows the values of collector efficiency of our present numerical model while assuming there is no silicone oil layer on top of the solar collector; and the third curve shows the values of collector efficiency of our present numerical model while assuming there is a 3 mm thick silicone oil layer present on top of the solar collector. Comparing these 3 curves, it can be clearly seen that under identical conditions, the presence of a thin layer (3 mm) of silicon oil improves the overall efficiency of the solar collector.

5. Conclusion

Directly absorbing stratified fluids, whilst in thermal contact, have been investigated and their performance reported for the first time. Silicone oil layer acts as a thermal barrier to emissions from nanofluid which helps in reducing the radiative and convective losses to the ambient. The presence of the silicone oil led to higher temperature rise (approx. 3.5 °C), as compared to the cases where no silicone oil was used. A silicone oil amount of 1 ml was found to be sufficient for the cases of nanofluids studied. In future, we plan to investigate a wider range of nanofluid concentrations and silicone oil layer thicknesses to identify optimum fluid pair specifications conducted with different volume fractions of the nanofluid and with different thicknesses of the silicone oil.

Conflicts of interest

The authors declare no conflict of interest.

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