Liquid layer envelope for reducing radiative losses in nanofluid-based volumetric receivers

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Abstract
At high flux conditions, surface absorption based solar thermal systems underperform owing to high overheat temperatures of surface (temperature difference between the surface and the working fluid). One of the ways by which this drawback could be addressed is by allowing direct interaction of solar radiation with the working fluid. In this context, nanoparticles (NP) laden fluid (nanofluids) have been shown to be promising candidates as direct absorption volumetric solar energy absorbers owing to their enhanced thermo-physical properties and high solar weighted absorptivity. However, the nanofluids inherently have high emissivity in the mid-infrared region thus not satisfying the conditions of solar selectivity.
In this study a layer of liquid (silicone oil) is placed above the nanofluid, which acts as a barrier against the infrared emissions from the nanofluid. Selection criterion for this liquid layer is high transparency in the visible solar spectrum and high absorption in the mid-infrared wavelength range. Thus the two conditions of solar selectively have been met by using two different liquid layers in direct thermal contact. On comparison of two results, it is seen that with silicone oil layer, the temperature rise is about 17% more as compare to without silicone oil layer.

Keywords: stratified fluid, nanofluid, silicone oil, heat transfer, solar energy.

1. Introduction
A large amount of solar energy (approx. 173,000 TW) is freely available energy on the surface of the earth, due to which a huge amount of research is going on to efficiently harness solar energy. For harnessing this energy solar thermal collectors have been used which are a kind of heat exchangers, in which the incident solar energy is absorbed by an absorber plate (usually a metal plate coated with black paint), converts it into heat and transfer the heat to the working fluid by conduction and convection heat transfer mechanism [Duffie and Beckman, 2003]. To run a power generation cycle, the temperature of the working fluid should be very high (around 200^{o}C to 300^{o}C), so high flux is incident on the solar collector [Lenert and Wang, 2012]. It is seen that at high flux conditions the efficiency of the surface absorption systems reduces, because of high

temperature difference between the absorber surface and the working fluid [Lenert and Wang, 2012]. In order to overcome this issue, the solar radiation may be absorbed by the working fluid itself [Lenert and Wang, 2012]. In this context, nanoparticle-laden fluid based solar collector, have been shown to be promising candidate and known as direct absorption based solar collector (DASC)[Tyagi *et al.*, 2009, Otanicar *et al*., 2010]. In order to understand the working mechanism of these volumetric solar receivers, researchers have proposed different configurations like gas-particle suspension [Miller *et al*., 1991 and Bertocchi *et al*., 2004], liquid films [Bohn *et al*., 2004] etc. But initially the micron sized particles were used in volumetric solar receivers, which have many challenges so the research later shifted to nanosized particles based volumetric solar receivers [Das *et al.*, 2007]. Tyagi *et al*., 2009, Otanicar *et al*., 2010 and Taylor *et al*., 2011, showed numerically and experimentally that the direct absorption based solar collectors have high efficiency than commercially available surface-based solar collectors. Literature suggested that the performance of the direct absorption based solar collectors depend on parameters such as the quantity of the nanoparticles dispersed in the base fluid, the material and the shape of the nanoparticle [Tyagi *et al.*, 2009, Otanicar *et al*., 2010, Taylor *et al.*,2011, Sani *et al*., 2011, Khullar *et al*., 2014,Hordy *et al*., 2014 and Bhalla *et al*., 2017] and most of the studies focused on the efficiency enhancement of the solar collector. However the aspect of making these collectors as solar selective is yet to be explored.
The solar selective design requires two conditions: (a) high absorptivity in the short wavelength (solar spectrum region, λ < 2.5 μm) and (b) low emissivity at high wavelengths (typically in the mid infrared region λ = 2.5 to 10 μm) [13-15]. Now, as the temperature of fluid increases, controlling the emissive losses becomes significant because the radiative losses are proportional to fourth power of the absolute temperature (i.e.T^4) and by controlling these losses there will be a significant improvement in the performance of the solar collector.
In the present experimental study we propose that the radiative losses can be reduced by using a layer of liquid (silicone oil (Sigma Aldrich, viscosity 50 cST at 25^oC)) above the nanoparticles laden fluid (Amorphous carbon (Sigma Aldrich, < 50 nm particle size, granular) dispersed in water), which will act as a barrier against the infrared emissions from the nanofluid. Amorphous carbon based nanofluid has been used for the experiments because literature suggests that graphite nanoparticles based fluid has broad optical spectrum which is helpful in absorbing large amount of solar irradiation. Selection criterion for this liquid layer is high transparency in the visible solar spectrum and high absorption in the mid-infrared wavelength range. Thus the aforementioned conditions of solar selectively can be met through stratified fluid (silicone oil + nanofluid) 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 cases the samples have been irradiated from the top in order to compare the thermal effect of both systems under similar operating conditions.

2. Theoretical Basis

The energy conversion process in the solar thermal system involves the conversion of solar energy into thermal energy. In this system, the incident flux is absorbed by the nanoparticles and the fluid. During this conversion process, radiative and convective losses occur at the top surface of the nanofluid as shown in Fig. 1(a), which results in reduction of the overall performance of the solar collector.

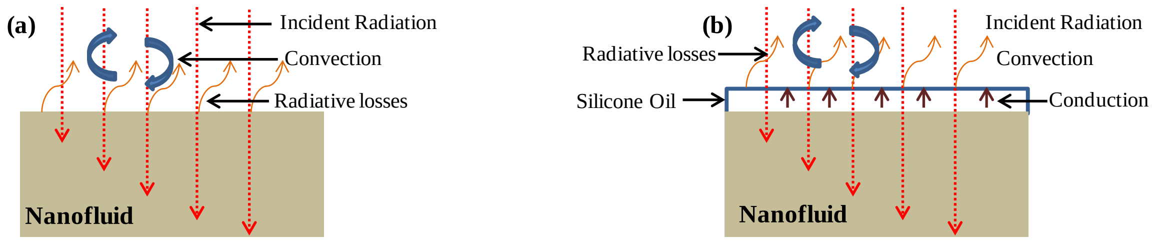


Fig. 1 Schematic of energy absorption and losses to the environment for (a) NASW/OSO and (b) NASWSO.

In order to overcome this issue and make a nanofluid solar selective, a stratified fluid (silicone oil) has been used in which a thin layer of silicone oil has been placed on the top surface of the nanofluid as shown in Fig. 1(b). In this stratified fluid case, when the nanofluid will get heated and will emit the radiations to the environment, the layer of silicone oil will absorb the emitted infrared radiations. Due to which the silicone oil will act as a barrier to the radiative losses from the nanofluid because of its thermo physical and optical properties.

3. Materials and methods

3.1. Preparation of nanofluid

In the preparation of nanofluid two step method has been used and same methodology has been adopted as used by Bhalla *et al*., 2017.

3.2 Optical properties of nanofluid and silicone oil

The optical properties of the nanofluid play a significant role in the nanoparticles laden solar collector. The optical property of the nanofluid and silicone oil for the short wavelength (0.3µm-2.5 µm) has been measured with UV-Vis spectrophotometer (Perkin Elmer Lambda 950) keeping sample thickness of 10 mm. Long wavelength band (2.5µm-25µm) is the region in which radiative losses take place, and the determination of the transmittance in this region will provide an idea about the magnitude of the losses in this region. The long wavelength transmittance has been measured by 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 (1µm-15µm) and from this small depth of penetration spectral transmittance of highly absorbing liquids can be determined.

3.3. Evaluation of photo thermal conversion

For the testing of stratified fluid a table-top experimental set up has been used. Figure 2 shows the major components of the experimental set up. A halogen lamp (make Philips, colour temperature 3400 K) has been placed on the top of the receiver to illuminate the sample and the flux from the halogen lamp has been measured with an optical power meter (8.5 W/cm^2) and thermopile detector (1918-R and 818P, Newport optical) by keeping short wave filter (SWF) on the top of thermopile detector. This SWF has been placed on the top of the cylinder so that only visible part of light reach to the sample or the heating of the fluid take place by visible spectrum of the light only. The material of the receiver plays a significant role in reducing heat losses to the environment. Due to which the receiver (glass container) is made up of glass because it has low thermal conductivity (1.4 W/mK). To measure the spatial temperature rise of nanofluid, three K-type thermocouples have been placed at three different locations in the receiver as shown in Fig. 2(c) and one thermocouple has been placed outside to measure the ambient temperature. Each thermocouple has been calibrated before the start of experiments with a water bath (at 0^oC and at 100^oC). The measured temperature from these thermocouples was read by data acquisition system (NI 9213, National Instruments) and was recorded by using Lab View 9.0.1.

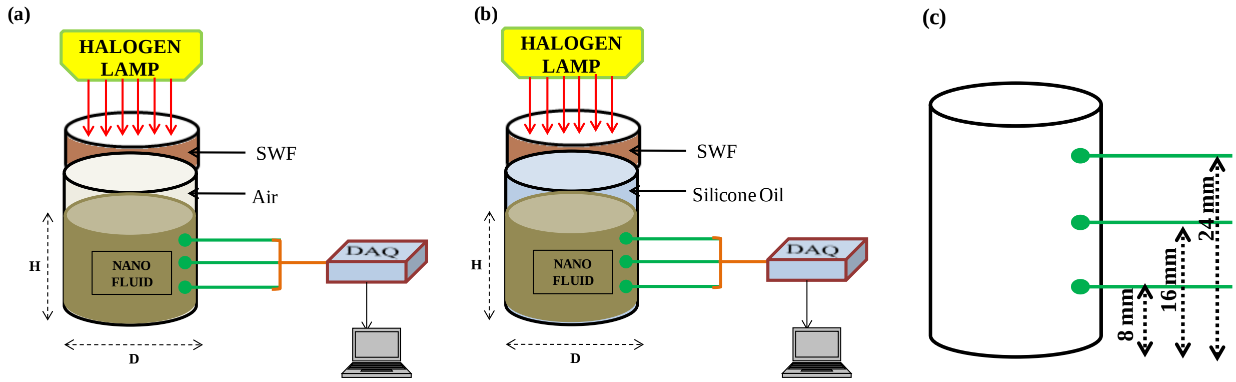


Fig. 2 Schematic of experimental setup consisting light source, thermocouples, DAQ, short wave filter for (a) nanofluid based absorption system without silicone oil [NASW/OSO], (b) nanofluid based absorption system with silicone oil [NASWSO], and (c) details of the three thermocouple locations

3.3.1 Experimental procedure

In the first case, freshly prepared nanofluid has been poured in the receiver and then short wave filter has been placed on the top of the receiver. After that the sample has been irradiated for 120 s and the temperature rise has been measured. In the second case, same set up has been used and similar procedure has been followed but in this case a layer of silicone oil (3mm) has been placed on the top of the nanofluid and the sample has been again irradiated for 120 s.

4. Results and Discussion

4.1 Optical properties of silicone oil and nanofluid

The measured transmittance of silicone oil in short wavelength range and long wavelength range are shown in Fig. 3(a). From this figure it is seen that silicone oil has high transmittance in the short wavelength range (especially in the visible region of the solar spectrum) and has very discrete absorption peaks in IR region even at very low depth of penetration. Figure 3(a) shows that silicone oil has very low absorptivity in the solar spectrum range and has high absorptivity in IR spectrum range, so the incident solar spectrum can pass through it without any optical loss but it will absorb the emitted radiations from the fluid. In the similar way, the measured transmittance of the nanofluid has been as shown in Fig. 3(b) and for the reference the measured transmittance of the base fluid has also been shown in Fig. 3(b). Figure 3(b) shows that water has 100% transmittance in the visible region i.e. it has 0% absorption in the visible region and with the addition of small amount of nanoparticle (20 mgl^{-1}) in the base fluid made the fluid absorptive.

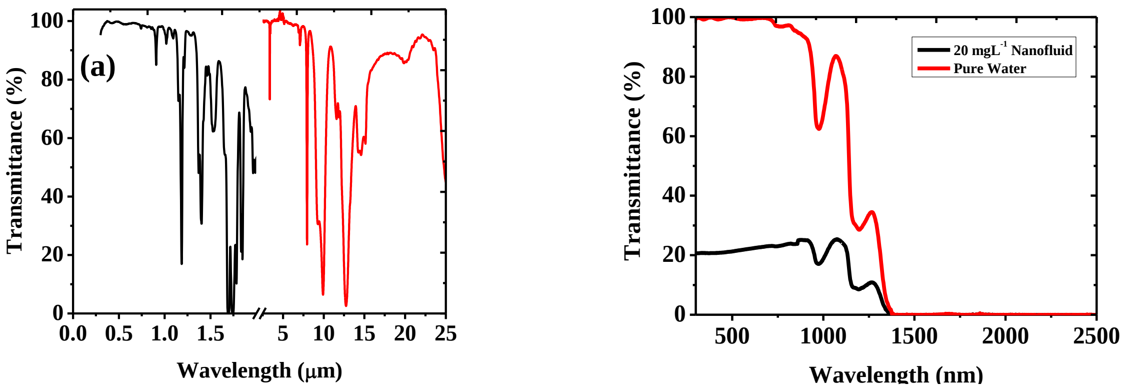


Fig. 3 (a) Transmittance spectrum of (a) silicone oil in short and long wavelength range, and (b) (b) pure fluid (water) and amorphous carbon based nanofluid (20 mgL^{-1})

4.2 Temperature rise of nanofluid based absorption system with and without silicone oil

The performance of 2 cases has been measured in this study - case (a) nanofluid based absorption system without silicone oil [NASW/OSO], and case (b) nanofluid based absorption system with silicone oil [NASWSO] has been studied by illuminating the system for 120 sec and the temperature rise of the nanofluid has been measured under identical conditions. The measured temperature of the nanofluid has been shown in Fig. 2(a) and Fig. 2(b). Figures 2(a) and 2(b) shows that the temperature of the nanofluid at the top side of the container is highest and it reduces along the depth of the container which shows that the incident flux has been absorbed by the nanofluid and the attenuation of the flux take place along the depth of the container. Furthermore, Fig. 2(c) shows the comparison of temperature rise of both cases under identical conditions. Figure 2(c) shows that with the presence of a layer (3 mm thick) of silicone oil above the nanofluid (which is corresponds to case (b)), the temperature rise is 5^{o}C more than case (a). This can be attributed to the fact that with silicone layer on the nanofluid, thermal trapping take place and which is helpful in reducing the convective and emissive losses to the ambient.

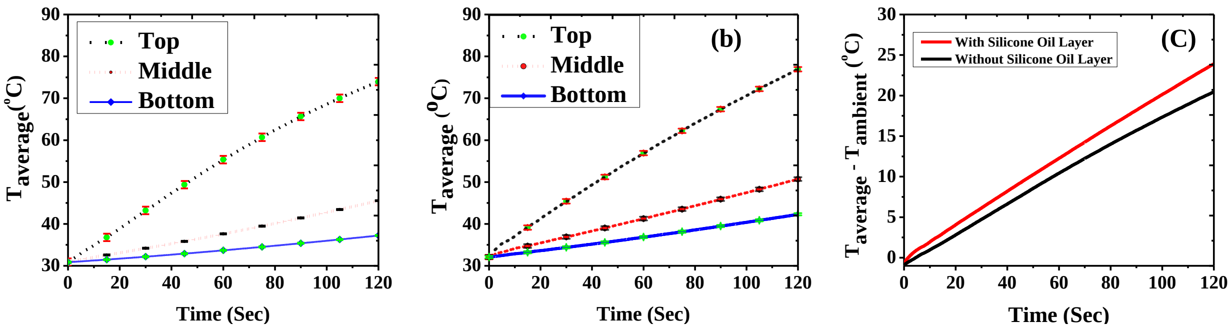
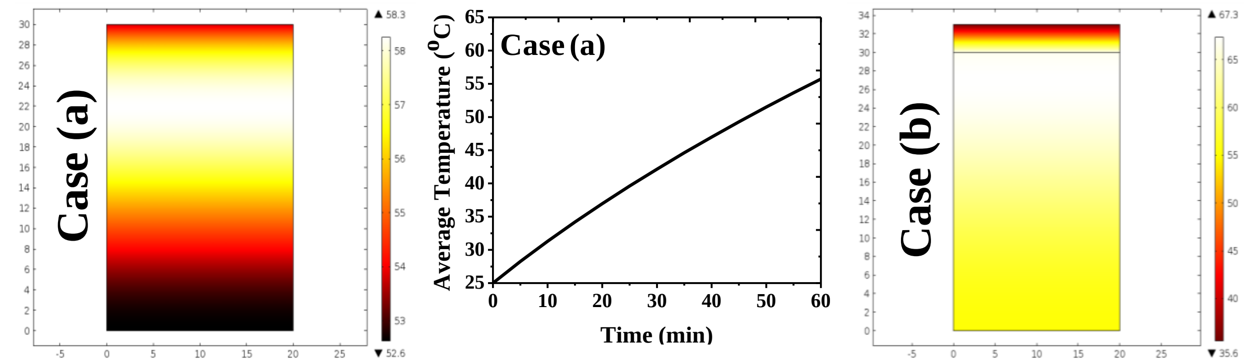


Fig. 4 Average temperature rise of (a) nanofluid based absorption system without silicone oil [NASW/OSO], (b) nanofluid based absorption system with silicone oil [NASWSO], and (c) comparison of average temperatures for both case (a) and case (b).



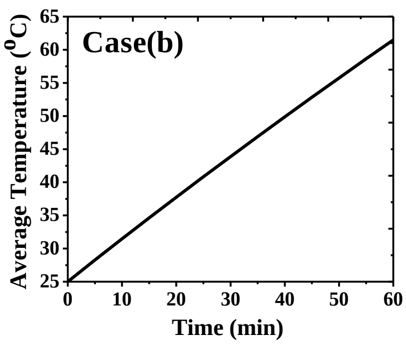


Fig. 5 Average temperature rise of (a) nanofluid based absorption system without silicone oil [NASW/OSO], and (b) nanofluid based absorption system with silicone oil [NASWSO].

In order to understand the physics of both cases, numerical simulation has been conducted by considering identical conditions. The results from the simulation have been as shown in Fig. 5. The simulation results, as seen in this figure, also following the same experimental trend i.e. with the presence of a layer of silicone oil the overall losses can be reduced. This is evident by the presence of much higher temperatures (relative to the case where no silicone oil is used).

5. Conclusion

In conclusion, we report first experimental study of direct absorption solar collectors using stratified fluids which are in thermal contact with one another. The experimental results show that layer of silicone oil act as a thermal barrier to emissions from nanofluid which helps in reducing the overall losses (radiative and convective losses) to the ambient. In the experimental and simulation study, 3 mm layer of silicone oil has been used and it shows that with this thickness of silicone oil temperature of the nanofluid is increasing, so in future a study can be conducted with different volume fractions of the nanofluid and with different thicknesses of the silicone oil. The thickness of the silicone oil is shown to have a positive impact on the performance of the nanofluid based solar thermal collector.

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