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Photothermal conversion of biodegradable fluids and carbon black nanofluids

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Abstract

The paper is devoted to the topic of direct absorption solar collectors (DASCs). The main focus is on comparing two kinds of working fluids that can be used in DASCs, namely carbon black nanofluids and biodegradable coffee colloids. At first, the fluids were tested by exposing them to artificial light (indoor experiments) and real solar irradiation (field experiments). The indoor experiments used a system of relatively large geometry, so most of the heat absorption occurred close to the irradiated surface. This resulted in a similar performance by both fluids. The field experiments involved a smaller system, and the light was concentrated by a solar collector. Here the nanofluid outperformed the coffee colloids. Next, the process was analysed using a theoretical analysis that gave good correspondence with the experiments. Finally, we extended the theoretical analysis to a DASC with a flowing fluid. The model was validated against results from the literature, but it also supported our experimental findings.

Keywords: nanofluids, solar energy, solar thermal technology, carbon black, biodegradable fluids, eco-friendly fluids, direct absorption solar collectors

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1. Introduction

Different techniques within solar thermal technology can be used to convert energy from the sun into heat. One of them involves direct absorption solar collectors (DASCs), which utilise fluids subjected to solar irradiation (see e.g. Gorji and Ranjbar [1]). The heated fluids are later transferred further into the system. As such, the solar thermal technology differs from the photovoltaic techniques that produce electricity.

Water is perhaps the most obvious choice as a heat transfer fluid in DASCs. There have, however, in the research literature been frequent attempts to replace water with fluids possessing superior properties. Here the appropriate candidates are “black fluids”, that is, liquids that offer better absorption of solar radiation. The paper by Minardi and Chuang [2] was, perhaps, the first that investigated this issue. In their work, they considered ink in water. More recent research papers, however, usually exploit fluids with suspended nanoparticles (so-called nanofluids).

Different types of nanofluids were investigated in the literature. Some examples are the following systems: copper-water [3, 4], aluminium oxide-water [5, 6, 7], TiO_2 , SiO_2 , CuO , or carbon nanotubes in water and in oil [8]. In our previous research, we studied carbon black (CB) nanoparticles [9, 10, 11] and iron oxide nanoparticles [12, 13] in water.

There is, however, another alternative, namely the use of biodegradable fluids. An interesting example is coffee colloids, which are widely available, inexpensive and eco-friendly. Moreover, they function without other drawbacks inherent to metallic nanofluids such as potential erosion [14, 15, 16] or nanoparticle deposition/clogging. Nevertheless, this topic has only been discussed in a few papers [17, 18, 11]. Therefore, they are the objective of this research.

In this paper, we aim to compare carbon black nanofluids with coffee colloids regarding potential applications in solar thermal energy. Our research was structured as follows. First, a stationary system consisting of a beaker filled with a nanofluid/coffee colloid was studied. The beaker was subjected to irradi-

ation by a halogen lamp that mimicked the solar radiation. This was done in a laboratory under controlled conditions. Different concentrations of the nanofluids were considered, and they were compared with the coffee colloids. This part of the paper resembles our previous paper [11], but this time we show that the
35 change of the set-up geometry has a significant influence on the conclusions.

In the second step, a similar set-up was subjected to real solar irradiation in field experiments. In addition, a parabolic solar collector was used to concentrate the light. This resulted in a high temperature increase; moreover, the conclusions were not the same as for the previous experiments with a halogen
40 lamp.

In the third step, we conducted a theoretical analysis of the studied process. At first, a simplistic model was suggested and validated against our laboratory experiments. Finally, a similar model was applied for studying a simple model of a DASC and validated against results from the literature. It was shown
45 that the choice of heat transfer fluid does not need to play an important role and the biodegradable coffee colloids may replace the CB nanofluids in some applications. It is also interesting to note that our simplistic mathematical model leads to results that are comparable with experiments.

2. Analysis of stationary fluids: indoor and field experiments

50 2.1. Fluid preparation

There are two kinds of fluids studied in this research. The first type was a nanofluid produced by dispersing CB in distilled water. CB was of type Timcal Ensaco 350G, and an image of the CB nanoparticles is shown in Fig. 1. This was obtained using a scanning electron microscope of the type Zeiss SUPRA
55 55VP S.

A weighted sample of CB was mixed with distilled water, together with the same amount of sodium dodecyl sulfate that was necessary to stabilise the nanofluid. At first, the suspension was mixed using a standard ceramic magnetic stirrer. The duration of the process was 20 minutes. Afterwards, a beaker with

60 the suspension was placed in an ultrasonic bath of the type Branson 3510. The duration of the sonication was 1 hour. The nanofluid obtained was stable for the subsequent months. It must be noted that a similar procedure was used in our previous works [9, 10, 13, 11], as well as by other researchers [19, 20, 21, 22].

We produced three different weight concentrations of CB nanofluid: 0.25%,
 65 0.50%, 1.0%. Thus, this research differed from our previous paper [11], where the focus was on higher concentrations.

Figure 1: Scanning electron microscopy image of the carbon black nanoparticles investigated in this research.

The second fluid was a coffee colloid obtained from Arabica coffee of the Tchibo brand. Figure 2 shows a SEM image of the dry coffee powder, and Fig. 3 shows a spectrum acquired via energy-dispersive X-ray spectroscopy (EDX).

70 Similar to our previous research [11], the coffee colloids were produced using a standard coffee brewer. The brewing process was run three times to maximise the extraction process. In our previous paper, different concentrations were tested and the main conclusion was that a simple increase in concentration leads to better results regarding the irradiation absorption. Therefore, in the
 75 present paper, we selected the highest concentration tested in [11], which was

Figure 2: Scanning electron microscopy image of the dry coffee particles.

Figure 3: Energy-dispersive X-ray spectroscopy of the coffee particles. The most dominant elements were carbon and oxygen.

15.0 g coffee powder dispersed in 300 ml of water.

2.2. Indoor experiments

The objective of the first part of the experiments was to investigate a relatively simple case, where a studied fluid (coffee colloid or nanofluid) was subjected to halogen lamp irradiation in a laboratory. The halogen lamp mimicked

the real solar irradiation. As such, the radiation spectrum of the lamp differed from the solar spectrum, but still, the experiments could be performed under controlled conditions.

Figure 4 shows a schematic of the experimental set-up. The fluid was placed
 85 in a beaker (denoted as A) whose inner diameter was 56 mm; the wall thickness was 2 mm, and the height was 120 mm. The height of the fluid was 105 mm. The beaker with the fluid was subjected to irradiation from the halogen lamp (B) that was located behind a protective and insulating screen (C). The height of the slot in the screen was 3 cm, and the distance between the light source
 90 and the beaker was 4 cm.

The temperature was measured by a thermocouple via a multi-logger thermometer of type Omega HH506RA. The thermocouple was immersed at the depth of 20 mm. During preliminary experiments, we tested different locations of the thermocouple, but the influence on the results was minor.

Figure 4: The schematic of indoor experiments (not to scale). A beaker with a studied liquid is subjected to halogen light.

95 This part of the research resembles our previous investigated reported in [11], as well as in [23, 9, 10]. There are, however, some important differences. At first, we used a beaker of different geometry. Also, the distance between the light source and the beaker was less than in [11]. The main objective was to check whether this change of design parameters will result in a similar performance.

100

The halogen lamp was a Cotech 400WV floodlight with an Osram light bulb. Figure 5 shows the intensity of the light irradiation measured as a function of distance from the lamp. The measurement was performed using a sensor from Linshang Technology.

Figure 5: Intensity of the halogen lamp vs. distance.

The fluid samples were irradiated for 7200 s. An example of temperature increase history is shown in Fig. 6 (denoted as “experiment” in the graph). Similarly, Fig. 7 shows an example of temperature increase history for one of the nanofluid samples.

We repeated each experiment at least four times, and Fig. 8 shows the final increase in temperature. This was recorded after 7200 s (when the process became steady). The figure compares different concentrations of the CB nanofluid with the coffee colloid.

The main observation is that the temperature increase is similar for all the concentrations of the nanofluid and coffee colloid. This differs from our previous paper, where the nanofluids outperformed the coffee colloid. There are, however, important differences in the design of the experimental set-up. In the present research, the irradiated area (if compared to the fluid height) was larger than the one used in our previous paper. Also, the intensity of radiation was higher

Figure 6: History of temperature increase (an example) for the coffee colloid sample during the indoor experiments. The results also validate the two mathematical models discussed in Section 3.

Figure 7: History of temperature increase (an example) for a nanofluid sample during the indoor experiments. The results are compared with the theoretical analysis discussed in Section 3.

due to the lower distance between the halogen lamp and the beaker. These two factors may have resulted in a greater heat loss to the surroundings.

120 In addition, the diameter of the beaker was larger if compared with our previous research so that most of the fluid may have stayed in a region not directly irradiated. Thus, the final temperature increase is also less dependent

Figure 8: The temperature increase for different fluids involved in the indoor experiments (NF: nanofluid; CC: coffee colloid). All the fluids (except for distilled water) result in a similar performance.

on the fluid properties.

This also shows that choice of a type of fluid and its concentration may be outperformed by the design of a DASC. In other words, it may be challenging to find an optimal fluid without considering its practical use later. Later in the paper, we discuss this issue more when theoretically investigating at performance of a simple DASC.

2.3. Field experiments

The second series of experiments was performed under real solar conditions. The nanofluid and coffee colloid were placed in two separate glass beakers and subjected to concentrated solar irradiation by using parabolic solar collectors. The schematic from one of the two set-ups is shown in Fig. 9, where the solar collector is denoted as A, the solar radiation as B and the beaker as C. We used two identical parabolic solar collectors with a diameter of 30 cm, with the studied fluids located in the focal points.

The objective was to run these two tests simultaneously under the same weather conditions. It must, however, be noted that the solar collectors may still have differed, especially in the light reflectivity from their surfaces. Furthermore,

140 the results were significantly influenced by a changing wind speed during the measurements.

The beakers had an inner diameter of 21 mm and a thickness of 1.5 mm. The length was 150 mm with the fluid height equal to 120 mm. Thus, we used smaller beakers than in the indoor experiments (larger beakers could significantly shield
145 the solar collectors from solar radiation). The temperature was measured in the same way as during the indoor experiments.

We selected only one concentration of CB nanofluid, namely 0.5% because the indoor tests did not reveal any important differences between the concentrations, and since our main objective was rather to compare the performance
150 of nanofluids vs. coffee colloids.

The experiments were performed close to the city of Bergen (western Norway) at $60^{\circ}18'41.2''\text{N}$, $5^{\circ}20'42.0''\text{E}$ in May and June in 2021, around noon. Only sunny days were selected for the experiments.

We did not use any solar tracking devices to adjust the orientation of the
155 collectors, so there was some inherited uncertainty of the measurements. Nevertheless, the duration of each test was short (maximum 10 minutes), and the largest discrepancy was observed only at the beginning. Also, we ran four tests on different days to assure repeatability. All the tests led to the same conclusions as shown in the following.

160 Figure 10 shows a history of temperature increase in the nanofluid and coffee colloid. An interesting observation is that the process is much more rapid than it was for the indoor experiments because the beam of the concentrated light was much more intense. In addition, the amount of fluid was also less in the field experiments. As a result, the boiling temperature was reached after a few
165 minutes.

In the case of nanofluids, we detected a crackling sound during the process. Most probably, this was caused by implosions due to a subcooled water boiling at the CB particles, something not observed for the coffee colloids. This indicates that the process of radiation absorption in nanofluids is more complex and occurs
170 locally on nanoparticle surfaces. The phenomenon did not happen during the

Figure 9: The schematic of the field experimental rig (not to scale). A beaker with a studied liquid is subjected to concentrated solar irradiation. The beaker is located at the focal point of a parabolic collector.

indoor experiments, where the light was not concentrated so that its intensity was significantly lower.

A summary of all the four experiments is shown in Table 1. The first two columns show the weather conditions at the beginning of each test (the solar irradiation and air temperature). This was obtained from the local weather station (Ytrebygda Weather Station). The next two columns depict the initial temperatures of the fluids, i.e., before the beakers were placed in the focal points of the collectors. The temperatures were always higher than the ambient temperature because the samples were allowed to stay under the sun until their temperature stabilised.

The last two columns show the measured time until the boiling commenced,

Figure 10: A typical history of fluids temperature during the field experiments using the solar concentrators. The results are compared with the theoretical analysis discussed in Section 3.

that is, the temperature became 100°C (also observed visually). It can be clearly seen that the nanofluid reached the boiling temperature faster.

Table 1: Outdoor results

No.	Solar irrad.	Temp. surround.	Init. temp. CC	Init. temp. NF	Time until boil. CC	Time until boil. NF
1	784 W/m^2	18.0°	32.2°	36.3°	945 s	875 s
2	744 W/m^2	15.7°	29.6°	33.2°	950 s	665 s
3	775 W/m^2	16.4°	30.7°	32.4°	760 s	745 s
4	768 W/m^2	25.7°	33.9°	34.4°	610 s	525 s

185 An interesting conclusion that can be drawn is that nanofluids are better candidates for the solar thermal energy technology if concentrated solar beams are used. This is due to the subcooled boiling.

3. Theoretical analysis

The objective of this section is to present a mathematical model and computational results that can later be used to speculate on the potential use of biodegradable fluids in DASCs. At first, however, we pay attention to the results of the rig irradiation and show a tool that can be potentially used for the modelling of this system. In the next sections, our model is further extended to the modelling of DASCs.

The performance of the indoor rig can be easily described using the theoretical analysis presented in our previous paper [11]. In the following, we recapitulate the main steps of the model. In addition, we modify the model so that it better corresponds to the experimental observations.

Figure 11 shows a schematic of the studied beaker with a zone (height h) that is directly irradiated. We assume that h is equal to the size of the slot in screen B (from Figure 4). We also state that the irradiated zone can be modelled as a cuboid (Figure (b)), according to [11]. The size $\bar{D}$ was derived in [11].

Figure 11: Theory

We begin the analysis with the simple energy balance:

$$mc \frac{dT}{dt} = q - \alpha A(T - T_o), \quad (1)$$

where m is the fluid mass, c is its heat capacity, T and T_o are the current fluid
 205 temperature and temperature of the surroundings, respectively. Furthermore, q
 is the absorbed heat due to the light, α is the heat transfer coefficient, and A is
 the total area.

Next, we use Beer-Lambert's law [1, 24, 25] to calculate the volumetric heat
 generation within the fluid:

$$I(x) = I_o \exp(-Kx) \Rightarrow q_v(x) = -\frac{dI}{dx} = I_o K \exp(-Kx), \quad (2)$$

210 where K is the extinction coefficient, and I_o is the incident irradiation intensity.
 The total heat generation in the whole irradiated zone can be found by the
 integration of the volumetric heat generation q_v between $x = 0$ and $x = \bar{D}$ (see
 also [11]):

$$q = I_o D h [1 - \exp(-K\bar{D})]. \quad (3)$$

In the above, I_o can be found by interpolation of Fig. 5 so that it is calculated
 215 for the distance that is equal to $b + (D/2 - \pi D/8)$ [11], where $b = 4$ cm in this
 research (i.e., the distance between the lamp source and the edge of the beaker).

Thus, we obtain a model that is called Model 1 in the following. This model
 is fully based on our previous work [11].

Nevertheless, the model can be extended by assuming that the incident in-
 220 tensity is not constant but varies with distance due to the circular shape of the
 beaker. In the subsequent sections, this extended model is called Model 2.

First, $I_o D h$ from Eq. (3) can be understood as the incident heat on the
 cuboid surface. This part of the equation can be replaced by (with $R = D/2$):

$$I_o D h \equiv 2h \int_0^{\pi/2} I(y) R d\phi, \quad (4)$$

that is, only one half of the circular side is irradiated. The curve in Fig. 5 can
 225 be approximated by a second grade polynomial so that:

$$I_o Dh \equiv 2hR \int_0^{\pi/2} (aR^2 \sin^2 \phi + bR \sin \phi + c) d\phi, \quad (5)$$

where $a = 217794 \text{ W/m}^4$; $b = 61541 \text{ W/m}^3$, $c = 6290 \text{ W/m}^3$ when using our
 lamp. Hence, Eq. (3) becomes:

$$q = 19.2 [1 - \exp(-K\bar{D})]. \quad (6)$$

Equation (1) can now be solved:

$$T(t) = T_o + \frac{q}{\alpha A} [1 - \exp(-\alpha At/(mc))], \quad (7)$$

where the initial and ambient temperatures are the same and equal to T_o .

230 The extinction coefficient for the investigated coffee colloid was estimated
 to be 53 m^{-1} [11]. This was found using the halogen lamp, thus it may not
 directly correspond to the solar spectrum. Nevertheless, we assume that it will
 not change significantly. Also, the extinction coefficient for CB nanofluids is a
 few orders of magnitude higher, i.e., between 10^4 and 10^5 m^{-1} [25]. Therefore,
 235 we assumed this coefficient to be $5 \cdot 10^4 \text{ m}^{-1}$ for our calculations.

The heat transfer coefficient α was estimated according to empirical rela-
 tions [26] for the Nusselt number. Using the geometry of the beaker and the
 surrounding air properties, we found:

$$\alpha = \beta \cdot 2.72(T - T_o)^{0.25}, \quad (8)$$

where β is a correction factor. We introduced it to the model to account for
 240 differences between empirical relations from the literature and our set-up.

The results, where Models 1 and 2 were used, are shown in Fig. 6. β was
 selected to be 1.9 (used only in Model 2). The figure shows a history of the
 temperature increase from the initial one, for the case where the coffee colloid
 was used. The results are compared with one of the experiments. An analogous

245 result is shown in Fig. 7 for the case of the nanofluid. The correction parameter β was increased to 2.25.

The new model (Model 2) better matches the experiments, especially when modelling a nanofluid. It is especially visible at the beginning of the process, where the rate of the temperature increase is rather underestimated in Model 1. During this initial stage, the heat loss plays a minor role so that the choice
250 of the correction coefficient β was less important. We must emphasise that this parameter may be case dependent (i.e., its choice may be treated as questionable), and it is thus interesting that there is still a good correspondence between the theory and experiments at the beginning of the experiments.

255 A similar mathematical model can also be developed for the outdoor experiments. In this research, we assumed that the beaker with a studied fluid is subjected to concentrated light irradiation with intensity:

$$I_o = \gamma \frac{A_c}{A_s} I_{sun}, \quad (9)$$

where A_c is the area of the parabolic solar collector, A_s is the area of the irradiated zone, and I_{sun} is the sun irradiation. The parameter γ accounts
260 for the inefficiency due to the limited reflectivity of the collector, heat losses, shading of the collector by the rig, reflection from the glass beaker, inaccuracies when placing the beaker in the focal point, the limited accuracy of estimating the size of the irradiated zone and so on. We selected the parameter γ to be 0.7 because it validated our experimental results well.

265 Equation (3) can be re-written to:

$$q = I_o A_s [1 - \exp(-K\overline{D})] = \gamma A_c I_{sun} [1 - \exp(-K\overline{D})]. \quad (10)$$

This shows that the absorbed heat does not depend on the size of the irradiated zone as long as it is smaller than the size of the beaker.

In addition, the heat loss from the beaker to the surroundings was modelled
270 using Eq. (8), and the temperature of the fluid as a function of time was found using Eq. (7). The results of the fluid temperatures are shown in Fig. 10 and

compared to the previously discussed results.

For the coffee colloid, the parameter β in the heat loss model was equal to 1.0, i.e., as in the literature. Thus, our whole mathematical model describes the real process surprisingly well. For the nanofluid, the parameter had to be increased to 6.0. A reason may be a local high temperature (probably around at least the boiling temperature) that results in an intensive heat loss.

It must also be noted that the mathematical model has one crucial advantage, which is its simplicity. This may indicate that similar models can be potentially exploited for other solar thermal energy applications. This is the topic of the next section.

4. Potential use for DASCs

In the present section, we show a theoretical analysis of the use of the coffee colloids and nanofluids in a DASC. The results were compared with results by Bardsgard et al [25], which were inspired by Otanicar et al [27].

We investigated a simple system that mimics a part of a larger DASC. The schematic is shown in Fig. 12. A system with a flowing fluid has length L , width w and height h , and its mass flow rate was $\dot{m}$.

In our first analysis, we use the same parameters as investigated in [25], i.e., $L = 0.05$ m, $w = 0.03$ m, and h varied in the simulations. Next, $I_o = 1000$ W/m² (= 1 sun), the velocity was 0.0026 m/s, and the properties of the fluid were the same as for water. The initial and ambient temperatures were $T_o = 25^\circ\text{C}$. The heat loss coefficient varied in [25] between 23 and 34 W/(m²°C). In our research, we selected the highest of these values because it fitted well when comparing the results. The main objective was to find the outlet temperature T_1 .

In our mathematical model, the energy balance was (a steady flow):

$$\dot{m}c(T_1 - T_o) = wLI_o[1 - \exp(-Kh)] - \alpha wL(T_{ave} - T_o), \quad (11)$$

where we assume an average temperature, $T_{ave} = 0.5(T_o + T_1)$, for the heat

Figure 12: Theory

loss calculation. From Eq. (11), it is then straightforward to find the outlet
 300 temperature.

Figure 13 shows the results (the solid curve) of the outlet temperature computed for various values of the stream height. The results refer to a CB nanofluid with $K = 5 \cdot 10^4 \text{ m}^{-1}$ and are compared to [25] (the black boxes). It is interesting to note that our simplistic model leads to very satisfactory results, without
 305 a necessity to run complex computational fluid dynamics simulations or costly experiments.

Figure 13: Theoretical analysis of a DASC (solid line) compared with [25] (boxes and circles). The literature results focus on two different scenarios that were not modelled by us.

Next, we used the same model for a sensitivity analysis of a DASC. For this, the height h was significantly increased to 1.0 and 3.0 cm, i.e., to values that correspond better to a real design. Also, the length L was similarly increased to 0.5 m. It must, however, be noted that this length increase does not influence the final result, and other values would also be possible. The width w was not changed.

In our computations, we compared the two studied fluids (nanofluids vs. coffee colloids) and the two aforementioned heights. This resulted in four different cases. Fig. 14 shows the results in the form of the outlet temperature dependence on the flow velocity.

Figure 14: Sensitivity analysis using a simplistic model of a DASC. The graph shows the influence of the system height, kind of fluid (NF: nanofluid; CC: coffee colloid) and flow velocity on the final temperature.

There are two interesting conclusions that can be drawn here. First, the lowest velocities increase the residence time so that the fluids were subjected longer to irradiation. Nevertheless, this also leads to higher heat losses due to the higher temperature and longer exposure time to the surroundings. Still, in the studied set-up, the heat loss did not manage to decelerate the process significantly.

A more interesting conclusion is that nanofluids are more clearly superior to coffee colloids if the fluid height is low. For the highest value of the height,

325 the results were relatively similar. The reason is that the penetration depth for
solar radiation is very low for nanofluids. Thus, most of the absorption occurs
in a thin layer of fluid, as also observed by, e.g., [25]. This may also explain
the results observed for our indoor experiments, where the performance of both
fluids was almost the same. It must be mentioned, however, that it does not
330 need to be a case for intense radiation that leads to local boiling on the particle
surface, as it occurred during our field experiments.

Concluding remarks

When designing DASCs, attention should be paid to the system geometry
so that most of the fluid is directly subjected to solar irradiation. In the present
335 research, this was illustrated by fluid “depth”: for systems where the depth
was higher, the final performance did not seem to be dependent on the kind of
fluid. On the other hand, the solar irradiation penetration in fluids can be very
low, especially for CB nanofluids. Here other kinds of fluids (e.g., biodegradable
coffee colloids) should be sufficient because they do not necessarily underperform
340 nanofluids regarding their thermal efficiency.

Nevertheless, this does not need to be the case if concentrated lights are
used, for instance, if solar collectors are exploited. The intense beam of light
may lead to local subcooled boiling on the particle surface. This leads to a
quick local temperature increase, which decreases the heat loss assuming that
345 the heated fluid is promptly evacuated to insulated parts of the system.

It should also be noted that DASCs can easily be theoretically described by
using relatively simple mathematical relations, as shown in the paper. Aspects
like complex fluid flows, heat transfer and subcooled boiling may be challenging
to describe analytically, but still, the results may not be far from reality.

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