AIP Advances

Use of biodegradable colloids and carbon black nanofluids for solar energy applications

Cite as: AIP Advances **11**, 055214 (2021); https://doi.org/10.1063/5.0053258
Submitted: 14 April 2021 . Accepted: 28 April 2021 . Published Online: 11 May 2021

A. Kosinska, B. V. Balakin, and P. Kosinski

Use of biodegradable colloids and carbon black nanofluids for solar energy applications

Cite as: AIP Advances 11, 055214 (2021); doi: 10.1063/5.0053258
Submitted: 14 April 2021 • Accepted: 28 April 2021 •
Published Online: 11 May 2021

A. Kosinska,[1,a] B. V. Balakin,[1,b] and P. Kosinski[2]

AFFILIATIONS

[1] Department of Mechanical and Marine Engineering, Western Norway University of Applied Sciences, 5020 Bergen, Norway
[2] Department of Physics and Technology, University of Bergen, 5007 Bergen, Norway

[a] **Author to whom correspondence should be addressed:** anna.dorota.kosinska@hvl.no
[b] **Also at:** Department of Thermal Physics, Moscow Engineering Physics Institute, National Research Nuclear University MEPhI, 115409 Moscow, Russia.

ABSTRACT

The conversion of solar energy to heat can be performed in direct absorption solar collectors, where the radiation from the sun is absorbed by a fluid. There are various types of fluids that can be used, and recently, nanofluids (i.e., liquids with immersed nanoparticles) have been investigated by researchers. Nevertheless, nanofluids have inherent drawbacks such as cost, toxicity, and clogging. This paper considers the use of fluids that are inexpensive and neutral to the environment, namely, coffee colloids. These types of fluids have already been tested for solar energy applications, but they have not yet been compared with nanofluids. In this research, we conducted a series of simple experiments where both coffee colloids and carbon black nanofluids were analyzed under the same conditions. According to our results, the thermal efficiency of coffee colloid and the nanofluid systems is, respectively, 12% and 16% greater than that of pure water. In addition to the experiments, we developed a mathematical model that is based on the Beer–Lambert law and a heat balance equation. Despite its simplicity, the model predicts the results relatively well.

I. INTRODUCTION

There are usually two techniques for utilizing solar energy: photovoltaic and solar thermal. The first one is based on the conversion of solar energy to electricity, while the second one is used to produce heat. The present paper is devoted to solar thermal technology. This type of technology uses a collector, where solar irradiation is directly converted to heat.

There are usually two types of solar collectors: a surface collector or a direct absorption collector (see, e.g., the study by Gorji and Ranjbar[1]). The first one comprises a solid surface that is exposed to solar irradiation and is thus the warmest part of the design. This is necessary for heating fluids, but it also results in heat loss to the surroundings.

The second possibility is the use of special fluids that absorb the heat directly, that is, without being exposed to the hot surface. This simplifies the physical processes and also significantly reduces heat loss. For this, nanofluids (i.e., liquids with nanoparticles) have gained the most popularity.

The main advantages of such nanoparticle systems are their high relative surface area and high absorption of solar radiation. They also have higher thermal conductivity than pure fluids. In addition, they are more stable than systems with larger particles, so they form fewer agglomerates.

Different types of nanofluids have already been tested for solar energy applications. For instance, Yousefi *et al.*,[2] Colangelo *et al.*,[3] and Kim *et al.*[4] used Al_2O_3-nanoparticles in water for flat-plate solar collectors. Similar designs were also studied by He *et al.*[5] and Jamal-Abdal *et al.*[6] with copper-water nanofluids. In addition, various researchers investigated nanoparticles such as TiO_2, SiO_2, CuO, carbon nanotubes in water, ethylene glycol, and oil[7] for other types of solar collectors (cylindrical, conical, parabolic, triangular, and evacuated tubes). An interesting topic of research was the influence of magnetic field on the process, i.e., when ferrofluids are used. Examples are papers by Balakin *et al.*[8] or Alssady *et al.*[9]

Finally, nanofluids and their flow were investigated theoretically, and examples are recent papers by Turkyilmazoglu.[10–12]

Nevertheless, nanofluids have some drawbacks. They pose a hazard to both environment and human health and are often expensive to produce.[13] Furthermore, their presence in flowing fluids may result in inevitable issues like clogging or deposition in systems of complex geometries. This can be mitigated by adding surfactants, but their quality often deteriorates at higher temperatures.[1] In addition, nanoparticles in fluids may lead to erosion wear when in contact with solid walls such as pipes.[14–16] Finally, nanofluids may be less attractive for applications where toxic materials should be avoided, e.g., water purification or intensification of chemical reactions.

There is, however, a potential alternative, namely, using colloids whose absorbance of electromagnetic waves is higher than that for water. This was suggested for the first time by Minardi and Chuang,[17] who investigated ink in water for a direct solar absorbing system.

Another similar possibility is using coffee colloids that are biodegradable, non-toxic, easy to obtain and produce, and inexpensive. Currently, such kinds of fluids in solar thermal applications are only tested in few research papers.[13,18]

Some other nanofluids, which are of low-cost and not harmful to the environment, have also been investigated but not for potential usage of solar energy. Hosseini and Mirzaei[19] considered montmorillonite clay for use in heat exchangers. Awua *et al.*[20] investigated bio-based palm kernel fiber nanofluids and their thermal conductivity properties. Finally, Ranjbarzadeh[21] examined thermal conductivity and stability of silica nanoparticles.

This indicates that the topic of using eco-friendly fluids for solar energy applications is rather under-explored. Our objective was to compare such fluids with "real" nanofluids in the same experimental setup, and we selected a simple system to eliminate other physical phenomena.

We chose carbon black nanofluids since they are relatively inexpensive and easy to produce. Moreover, they have not been widely tested for solar applications except in a few papers.[22–24] As they are an environmentally neutral fluid, we select the aforementioned coffee colloids.

II. THE EXPERIMENTAL SETUP

The schematic of the experimental setup is shown in Fig. 1. It consists mainly of a beaker with the studied fluid (denoted by A in the figure). The inner diameter of the beaker was 22 mm, and the height of the fluid was 135 mm.

The fluid in the beaker was irradiated using a halogen lamp (400 W), denoted by B in the figure. Thus, the setup resembles the one used by other researchers.[22,23,25]

The radiation from the lamp was investigated using a Linshang LS122IT portable power meter, and the measurement of radiation intensity is shown in Fig. 2. This was measured along the main beam of the lamp by varying the distance from the light source. In the experiments depicted in Fig. 1, the beaker was located at a distance of 80 mm from the lamp. It was irradiated by the lamp, as shown by the arrows. According to our previous analysis,[26] this distance is significantly larger than the thermal boundary layer that forms on the lamp face. This indicates that the potential heating of the beaker due to natural convection did not occur.

The radiative spectrum of the halogen lamp was also previously investigated by us,[26] and this revealed a maximum radiative power

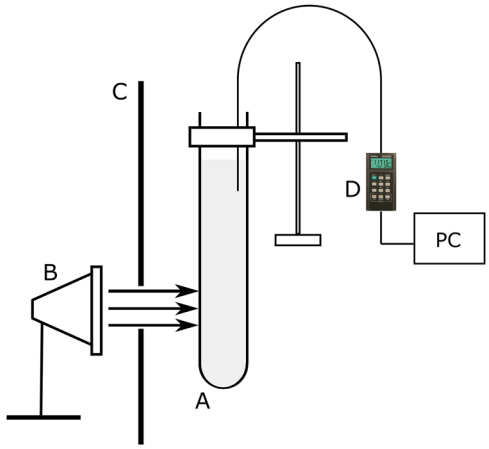

FIG. 1. Schematic of the experimental rig (not to scale).

for a wavelength of around 1000 nm. This value is of importance later in the paper when discussing the extinction coefficient. It must be noted that the use of the lamp does not essentially correspond to practical applications with the real solar spectrum. Nevertheless, our setup makes it possible to obtain repeated results under controlled laboratory conditions.

The halogen lamp was placed behind an insulating screen (denoted by C in the figure) to allow only a selected part of the beaker to be directly subjected to the light. In addition, this was carried out to decrease the heating of the experimental setup, such as the thermocouples, and the surrounding air. The height of the slot in the screen was 30 mm.

The temperature of the fluid was measured using a thermocouple connected to a multi-logger thermometer (type: Omega HH506RA) and a personal computer. This system is denoted by D in the figure.

Two kinds of fluids were used in the research: (i) coffee colloids (arabica coffee, the Tchibo brand) and (ii) carbon black nanofluids.

Pictures of the coffee powder, using an optical microscope (Nikon SMZ800), are shown in Fig. 3. The coffee colloids were prepared by using a standard home coffee brewer. In order to extract most of the organic material from the coffee powder, the process was

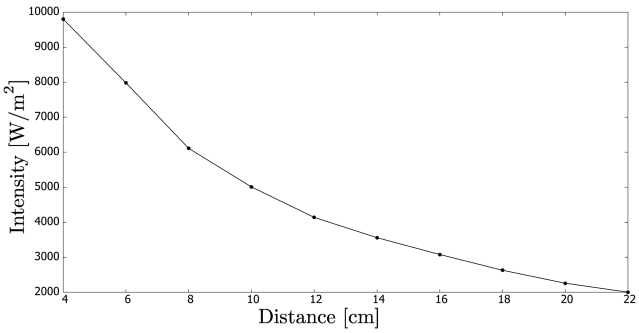

FIG. 2. Intensity of radiation vs distance emitted by the halogen lamp used in the experiments.

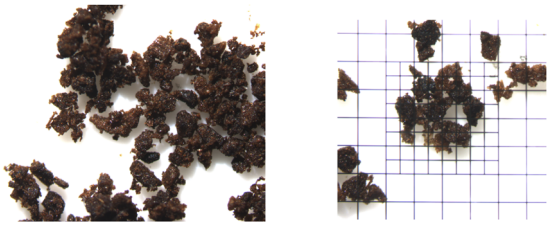

FIG. 3. Microscopic images of the investigated coffee powder. The grid cell size in the right image is 1 mm (the largest cells).

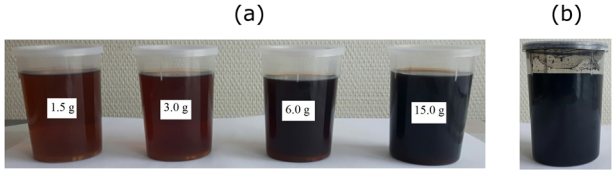

FIG. 4. (a) Coffee colloid samples: 1.5, 3.0, 6.0, and 15.0 g of arabica coffee dispersed in 300 ml water and (b) the carbon black nanofluid sample: concentration 1.0 wt. %. The other carbon black nanofluids are visually the same.

repeated three times, that is, coffee colloids were circulated back into the brewer. The coffee samples were weighed as follows: 1.5, 3.0, 6.0, and 15.0 g. The amount of water (distilled) was 300 ml. Figure 4(a) shows images of the different samples of coffee colloids.

For the preparation of carbon black nanofluids, we used a similar technique to our previous studies,[22,23,27] which has also been used by other researchers.[28–31] At first, a specified amount of carbon black (Timcal Ensaco 350G) was weighed and placed in distilled water. The properties of the powder were investigated in our previous paper.[22] In addition, the same amount of sodium dodecyl sulfate (SDS) was added to stabilize the nanofluid later. The suspension was mixed for 20 min using a ceramic magnetic stirrer. Next, it was sonicated in an ultrasonic bath (Branson 3510) for 60 min.

The following concentrations were produced: 0.5, 1.0, 1.5, and 2.0 wt. %. The obtained nanofluid was stable, that is, no sedimentation of carbon black particles was visually observed for at least a few weeks. Figure 4(b) shows a sample of one of the produced nanofluids.

III. THEORETICAL ANALYSIS

At first, an attempt was made to describe the process theoretically, supported by simple experimental measurements. We assume the fluid is a semi-transparent medium irradiated by a thermal radiation of a wavelength of 1000 nm, that is, corresponding to the maximum thermal radiation emitted by the lamp.

We state that the medium is one-dimensional and the highest radiation intensity, I_o (dimensions are [power/area]), occurs at coordinate $x = 0$. For higher values of x, i.e., as the radiation propagates within the medium, the intensity is attenuated according to the Beer–Lambert law,[1,24,32]

$$I(x) = I_o \exp(-Kx), \tag{1}$$

where K is the extinction coefficient, which is also the reciprocal of the penetration distance. This coefficient is a summation of absorption and scattering coefficients and depends on the wavelength.

In our research, we decided to create a simplistic model. The extinction coefficient was found by measuring intensities at coordinate $x = 0$ and after the light has passed through the studied fluids. For this, we used a cylindrical glass beaker of a known diameter. The measurements were repeated a few times, by varying the distance from the light (i.e., different values of I_o) and at various points in the fluid column. Thus, our extinction coefficient does not essentially correspond to monochromatic radiation.

We focused only on the coffee colloids because the studied carbon black nanofluids had very high values of the extinction coefficient that they became non-transparent when using our setup. Nevertheless, this coefficient for carbon black nanofluids was theoretically studied in our recent paper,[24] and therefore, it was less necessary to investigate this issue again. According to our previous work, the extinction coefficient resulted in rather high values of the order 10^4–10^5 m^{-1}.

In the end, by using Eq. (1), we calculated the extinction coefficient and, the results are shown in Fig. 5.

We compared the results to that of distilled water (the first point in the graph). It is interesting to note that the average value (37 m^{-1}) is similar to the one found in the literature (36.3 m^{-1}) for a wavelength 1000 nm.[33–35] This should indicate that the other experimental measurements were also satisfactory, even though we used a rather simple technique for the determination of this coefficient.

Next, we return to our experimental rig discussed in Sec. II and sketched in Fig. 1. We state that the irradiated domain has a disc-size, as depicted in Fig. 6(a). The height of the domain h is the same as the slot shown in Fig. 1.

We also assume that the initial intensity I_o is distributed uniformly on the cylindrical side of the beaker [see Fig. 6(b)] and the radiation propagates into the fluid as shown by the arrows. Due to the circular shape of the cross section, the central region will oppose the highest "depth" of the fluid (equal to the inner beaker diameter D), with no fluid at the edges. For simplicity, we state, however, that the fluid depth is the same for all the "arrows" and equal to the average beaker diameter. This average diameter can be found by averaging a function that represents the circular shape of the beaker [see Fig. 6(d)]. This results in $\overline{D} = 2 \times \pi D/8 = \pi D/4$.

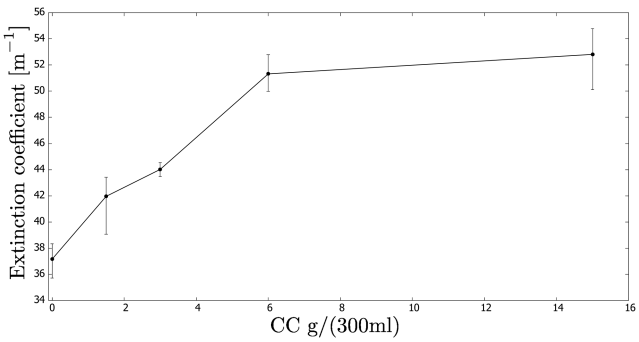

FIG. 5. Extinction coefficient for different coffee colloids (CCs).

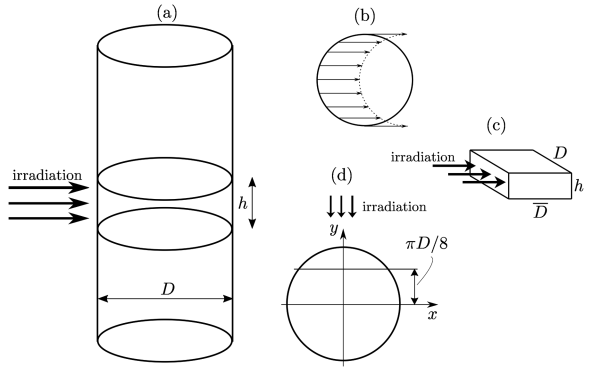

FIG. 6. Theoretical analysis: (a) the irradiated region has a disc shape, and (b) the radiation travels in the fluids along straight lines. (c) The irradiated region is modeled as a cuboid, where (d) side $\overline{D}$ is twice the average circle radius $\pi D/8$.

Therefore, we can state that the irradiated domain is a cuboid of size $D \times \overline{D} \times h$, where the irradiated area is $D \times h$. This is shown in Fig. 6(c). In addition, we assume the process to be steady, that is, the obtained heat generation is constant.

Furthermore, we use Eq. (1) to calculate the volumetric heat source (dimension: [power/volume]), from $q_v(x) = -dI/dx$. Thus, the total heat generation in the analyzed element is as follows:

$$q = I_o KDh \int_0^{\overline{D}} \exp(-Kx)dx = I_o Dh\left[1 - \exp(-K\overline{D})\right]. \quad (2)$$

As mentioned previously, the beaker was located 80 mm from the lamp, which corresponds to a light intensity of 6110 W/m^2 (see Fig. 2). However, in our mathematical model, the irradiated fluid has a cuboid form. Thus, we can state that the real (average) distance is increased by $(D/2 - \pi D/8)$, which is 2.4 mm when using our setup. Therefore, I_o decreases to around 5980 W/m^2.

Next, we state that the heat generation is used solely for heating the whole fluid in the system minus the heat loss to the surroundings. This results in a simple energy balance,

$$mc\frac{dT}{dt} = q - \alpha A(T - T_o), \quad (3)$$

where m is the mass of the fluid, c is the fluid heat capacity, T is the temperature of the fluid (i.e., we assume the temperature to be uniform in the whole system and is only dependent on time), T_o is the temperature of the surroundings, α is the heat transfer coefficient[36] that is constant for the whole system area, and A is the outer surface area of the studied fluid (i.e., the beaker). In our experimental setup, area A was equal to 0.0097 m^2, and mass m was 0.05 kg.

Solving Eq. (3) results in

$$T(t) = T_o + \frac{q}{\alpha A}\left[1 - \exp(-\alpha At/(mc))\right], \quad (4)$$

where the initial temperature is the same as the temperature of the surroundings. For $t \to \infty$, the final temperature becomes

$$T_f = T_o + \frac{I_o Dh}{\alpha A}\left[1 - \exp(-K\overline{D})\right]. \quad (5)$$

The heat transfer coefficient α that models the heat transfer from the beaker to the surrounding air was estimated using empirical relations of the Nusselt number. Assuming that the surroundings had a temperature equal to the initial temperature of the system and using corresponding air properties, as well as our system geometry, α became ≈4.45 W/(m^2 K).[36,37] In principle, the coefficient can be further tuned by validating against experiments. It must be, however, noted that the coefficient will also depend on the location in the beaker and time, i.e., it is not constant. Therefore, it was not modified in this research.

The fluid properties were assumed to be the same as those of water, that is, not influenced by the presence of the solid phase. The properties of coffee colloids are perhaps less available in the literature, but the concentration of the solid phase was also rather low, so the impact would be marginal. Finally, the model is already based on many assumptions, so the further tuning of the model will not lead to superior results.

The above-mentioned model also allows for the estimation the thermal response time. This can be defined as the time when the temperature increases, $(e - 1)/e \approx 63.2\%$. From Eqs. (4) and (5), the thermal response time is as follows:

$$\tau = \frac{mc}{\alpha A}, \quad (6)$$

which does not depend on optical properties of the fluid. In the present research, τ becomes 4853 s. This value is compared to our experimental results later in the paper.

Figure 8 shows the results of the modeling of the coffee colloid irradiation (the graph with crosses). It must be noted that the graph begins at 0° so that it depicts an increase from the initial temperature, i.e., $(T_f - T_o)$, from Eq. (5).

The graph focuses solely on coffee colloids because the absorption coefficient is readily available from our measurements. However, for carbon black nanofluids, the final temperature can also be estimated by assuming very high values of K in Eq. (5). For $K \to \infty$, the temperature increase becomes 84 °C, which is significantly more than that for the coffee colloids even with the highest concentration.

According to the simplistic theoretical analysis, this temperature increase does not depend on nanofluid concentration because K is high enough for all concentrations. According to our experimental results, analyzed in Sec. IV of the paper, this statement is, however, not fully correct.

IV. EXPERIMENTAL RESULTS OF IRRADIATION

Figure 7 depicts histories of temperature measured in three selected fluids: (i) distilled water (as the benchmark), (ii) coffee colloid (the highest studied concentration), and (iii) nanofluid (concentration 0.5%). This figure is shown as a demonstration of how the process develops over time. Similar to Sec. III, the y-axis begins at 0° so that it shows an increase from the initial temperature. We state that the terminal temperature is reached in the studied system after about 5100 s (for all the fluids).

According to the graph, the carbon black nanofluid shows the best performance. The coffee colloids show weaker performance; nevertheless, the result is quite decent if compared with that of distilled water.

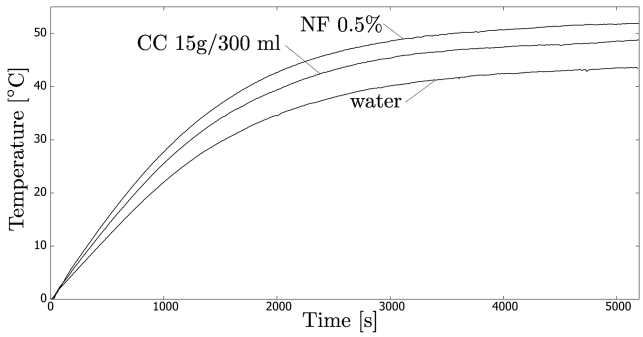

FIG. 7. Temperature increase vs time for three different fluids: distilled water, coffee colloid (CC) at 15 g/300 ml, and nanofluid (NF) at a weight concentration of 0.5%. As expected, irradiation of water results in the lowest temperature increase.

The final temperature increase can be treated as the most important parameter representing the performance of investigated fluids. Therefore, in Fig. 8, we show the final temperature increase (for time 5100 s, as mentioned previously) for different concentrations of coffee colloids (note that 0.0% corresponds to the distilled water). The experimental results are shown by the graph with dots. The results are compared to the theoretical analysis, discussed in Sec. III of the paper.

According to the figure, the highest concentration leads to the best result. The difference between the experiments and the theory is a few degrees Celsius, which is very satisfactory considering the simplicity of the theoretical model. We remind here that the theoretical analysis was supported by empirical measurements of the extinction coefficient. This also somewhat confirms that volume absorption is the main mechanism in the process.

One of the reasons for the discrepancy between the theory and experiments is the choice of the heat transfer coefficient α. At first, the temperature of the surroundings was rather larger than the initial temperature because the radiating lamp also influences the temperature of the air around the beaker. This decreases the heat loss, that is, α can be actually lower, i.e., the final temperature obtained in the model may be underestimated. This may explain the discrepancy between the experiments and theory for the lowest concentrations in Fig. 8.

On the other hand, the irradiated zone is subject to very high local temperatures. This is especially important for high values of the extinction coefficient, e.g., for high concentrations. In this case, the heat loss is more intense so that the real value of α may be locally higher.[24,38] Thus, the theoretical results may be overestimated for the highest concentrations (see Fig. 8).

Furthermore, the simplified model assumes a uniform temperature in the whole system, which is not the case in reality. This is again especially a case for the fluids with large values of the extinction coefficient. Finally, the model does not account for natural convection that occurs in the fluids.

Next, we show the results of carbon black irradiation, where we investigate the influence of concentration. This is depicted in Fig. 9. This time, we observe a rapid increase in the final temperature for very low concentrations. For higher values of concentration, the process seems to be less dependent on concentration, with a potential maximum around 0.5%.

In Sec. III, we mentioned that the theoretical temperature increase is 84 °C. This is referred to all nanofluids because their extinction coefficient is high. This also means that the penetration distance, that is, the reciprocal of this coefficient, $L = 1/K$, is low so that $L \ll \overline{D}$. In such a case, the total heat absorbed by the fluid can be computed by modifying Eq. (2) to the following form:

$$q = I_o D h[1 - \exp(-KL)], \tag{7}$$

since most of the heat absorption occurs only until the penetration distance. It can also be concluded that the heat absorption should be the same irrespective of the extinction coefficient (or the nanofluid concentration). To some extent, this is seen in Fig. 9 because the temperature increase does not differ much for the studied concentration. In addition, similar results were reported in the literature (see the review paper by Gorji and Ranjbar[1]), that is, a significant improvement in the process for very low particle concentrations.

Considering also the fact that the theoretical temperature increase of 84 °C differs more from the experimental observation than it does for the coffee colloids, we can conclude that the heat absorption process is essentially more complex when using nanofluids. The first possible explanation is that for higher particle

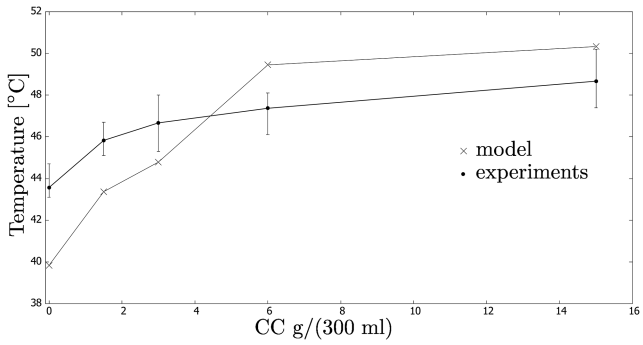

FIG. 8. Final temperature increase of coffee colloids as a function of their initial concentration. The figure compares the experimental results (solid dots) with modeling/theory (crosses).

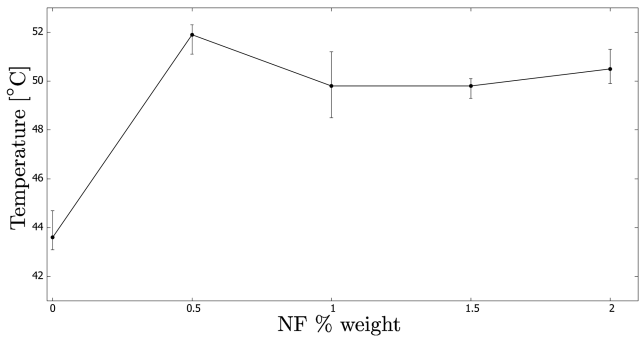

FIG. 9. Final temperature increase of nanofluids as a function of their initial concentration.

concentrations, the absorption occurs in a very thin layer of the fluid close to the outer surface. This has already been discussed above when analyzing the coffee colloids. It must be emphasized, however, that for nanofluids, this phenomenon is more intense due to very high heat absorption. Thus, this unwanted process will hinder obtaining high temperatures in the system, so some optimal concentration is expected.

It must also be mentioned that for high particle concentrations, the process of natural convection in the body of the fluid is more complex in the presence of particles. At first, the high local heat absorption increases the temperature gradients so that the natural convection is also more intense. Thus, we could expect the process to occur faster for high concentrations. On the other hand, the particles (especially for high concentrations) may hinder the fluid flow, making the process even more complex and resulting again in some optimal concentration.

Finally, even more complex issues such as subcooled boiling may occur, especially in the zone that is directly irradiated. As a result, the formation of gas bubbles will intensify the convective currents in the system.

An interesting issue, already mentioned in Sec. III, is the response time of the system. According to our theoretical model, the response time does not depend on the optical properties of the system [see the discussion under Eq. (6)].

Figures 10 and 11 show the experimental results of the response time for the coffee colloids and nanofluids, respectively. We show the dependence of the response time vs concentration.

According to the figures, the carbon black nanofluids result in shorter response times than the coffee colloids. This supports the previous conclusions that showed higher temperatures for the nanofluids, that is, the process was more intense. Nevertheless, for both kinds of fluids, the results are relatively close to each other. The average difference was roughly 100 s, which constitutes rather a low fraction of the whole process duration. It is also interesting to note that the obtained experimental measurements differ significantly from the theoretical results shown in Sec. III (=4883 s), i.e., the process is around four times faster in reality. A possible reason is the lack of natural convection in the mathematical model that intensifies heat transfer in the system and results in shorter process times.

Finally, in this section, we investigate the thermal efficiency of the process. It can be computed from the ratio of the heat absorbed by the fluid to the energy irradiated. Using the same notation as in Sec. III, we define efficiency as follows:

$$\eta = \frac{mc(T_f - T_o)}{IDht_f}, \tag{8}$$

where T_f is the final temperature (measured at ≈5100 s) mentioned above. It must be noted that this model differs from the one used by Alberghini *et al.*,[18] whose research was similar to ours. In their model, heat losses were also included. Thus, their efficiency would be larger than ours.

For coffee colloids, the results are shown in Fig. 12. The shapes of the graphs are essentially the same as the previously studied temperature increases, but we show these graphs separately to elucidate them.

The radiated zone was rather small in comparison with the size of the beaker. As mentioned previously, this was carried out to diminish irradiation of the equipment elements such as the thermocouples. As a result, the heating process is essentially slower so that heat loss will be more significant. That also decreases the efficiency of the process.

Despite this drawback, the obtained efficiency was decent: higher than 50% for the highest concentration. In addition,

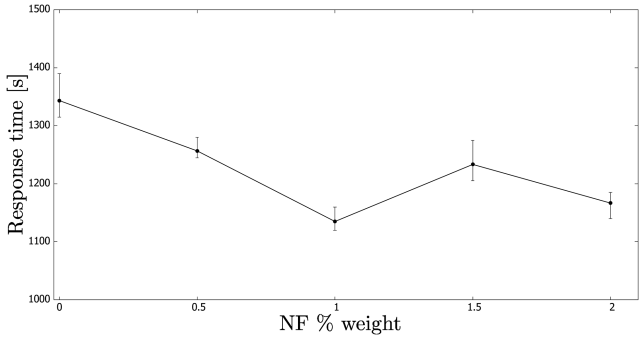

FIG. 11. Response time of the system containing nanofluids vs their concentration.

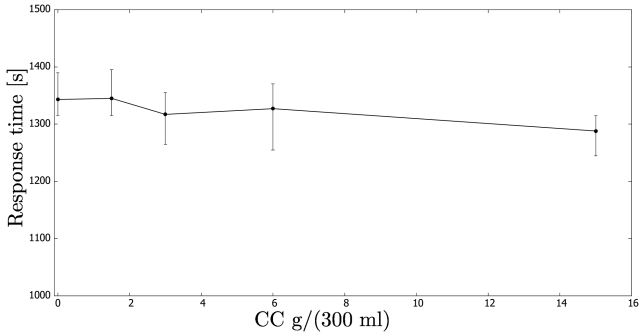

FIG. 10. Response time of the system containing coffee colloids vs their concentration.

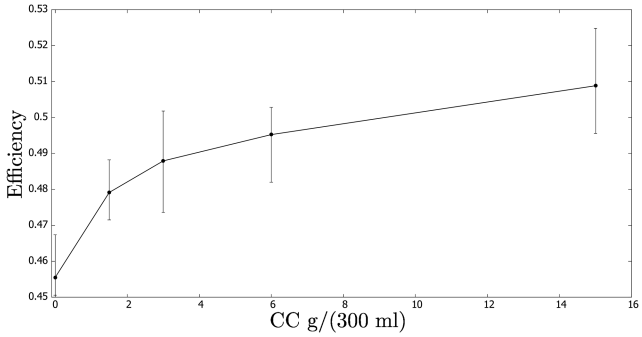

FIG. 12. Process efficiency of coffee colloids as a function of their initial concentration.

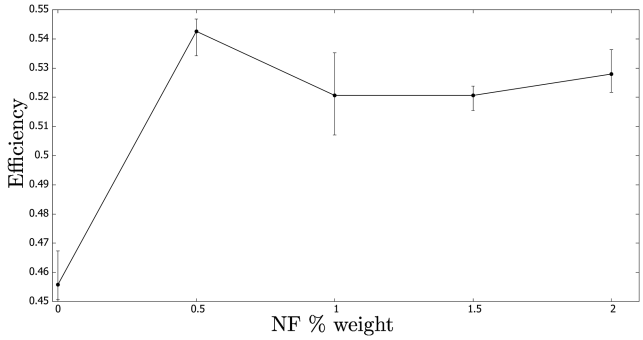

FIG. 13. Process efficiency of nanofluids as a function of their initial concentration.

the efficiency increase is around 12% in comparison with that of pure water.

For carbon black nanofluids, the results are shown in Fig. 13. At first, we observe that the highest efficiency (for a concentration of 0.5%) is around 16% more than that for pure water, i.e., 4% more than that for coffee colloids. In addition, the highest efficiency (52.8%) is less than that obtained by Jin *et al.*,[25] who used a similar experimental setup. Nevertheless, they used an evacuated-tube, where convective heat loss to the surroundings is also less. In addition, the light intensity was higher in our experiments, so the absolute temperatures were also higher. This further increased the heat loss to the surroundings, so the efficiency suffered. Finally, Jin *et al.* used gold nanoparticles that have different absorption properties.

On the other hand, our results on nanofluids compare well with those of the study by Otanicar *et al.*[39] or with computer simulations by Parvin *et al.*[40] They used graphite particles that are chemically similar to the carbon black used by us. It is interesting to note that the results are similar even though we used a very different experimental setup compared to Otanicar *et al.*

It is also interesting to note that a similar experimental setup was also used in one of our previous papers.[22] In addition, carbon black nanofluids were used for studying boiling processes. The obtained efficiency was higher than that in the present paper. Nevertheless, the process was very rapid because the whole beaker was subjected to intense irradiation. As a result, the process became steady after a much shorter time than in the present paper.

V. CONCLUDING REMARKS

In this research, we compared the performance of coffee colloids and carbon black nanofluids for potential application in solar thermal technology. It must be noted that our investigation used a simple experimental rig so that it was possible to eliminate other phenomena and focus only on solar irradiation in the studied fluids.

According to our research, carbon black nanofluids outperform coffee colloids if we consider the obtained temperature of the system and thermal efficiency. On the other hand, systems with coffee colloids are easier to predict using theoretical analysis, in addition to the obvious advantages such as low cost, no toxicity, and no particle deposition. The main reason is that coffee colloids are "simpler:" the fluid is essentially single-phase, and heat absorption can be described using the basic Beer–Lambert law.

For nanofluids, high local temperature occurs (in the directly irradiated zone), and this region is very close to the external wall of the system. Thus, the high temperatures obtained in the system with nanofluids can be disadvantageous in some cases due to higher heat loss. In addition, this may deteriorate the nanofluid, especially if surfactants are used. Thus, the better performance of the nanofluids does not necessarily mean that they are always superior to economical and biodegradable coffee colloids.

ACKNOWLEDGMENTS

This study was supported by the Russian Science Foundation (Project No. 19-79-10083). In addition, we express our gratitude to Dr. Pavel G. Struchalin for useful remarks.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

[1] T. B. Gorji and A. A. Ranjbar, "A review on optical properties and application of nanofluids in direct absorption solar collectors (DASCs)," Renewable Sustainable Energy Rev. **72**, 10–32 (2017).
[2] T. Yousefi, F. Veysi, E. Shojaeizadeh, and S. Zinadini, "An experimental investigation on the effect of Al_2O_3–H_2O nanofluid on the efficiency of flat-plate solar collectors," Renewable Energy **39**, 293–298 (2012).
[3] G. Colangelo, E. Favale, A. de Risi, and D. Laforgia, "A new solution for reduced sedimentation flat panel solar thermal collector using nanofluids," Appl. Energy **111**, 80–93 (2013).
[4] H. Kim, J. Kim, and H. Cho, "Experimental study on performance improvement of U-tube solar collector depending on nanoparticle size and concentration of Al_2O_3 nanofluid," Energy **118**, 1304–1312 (2017).
[5] Q. He, S. Zeng, and S. Wang, "Experimental investigation on the efficiency of flat-plate solar collectors with nanofluids," Appl. Therm. Eng. **88**, 165–171 (2015).
[6] M. T. Jamal-Abad, A. Zamzamian, E. Imani, and M. Mansouri, "Experimental study of the performance of a flat-plate collector using Cu-water nanofluid," J. Thermophys. Heat Transfer **27**, 756–760 (2013).
[7] A. H. Elsheikh, S. W. Sharshir, M. E. Mostafa, F. A. Essa, and M. K. Ahmed Ali, "Applications of nanofluids in solar energy: A review of recent advances," Renewable Sustainable Energy Rev. **82**, 3483–3502 (2018).
[8] B. V. Balakin, O. V. Zhdaneev, A. Kosinska, and K. V. Kutsenko, "Direct absorption solar collector with magnetic nanofluid: CFD model and parametric analysis," Renewable Energy **136**, 23–32 (2019).
[9] M. Alsaady, R. Fu, Y. Yan, Z. Liu, S. Wu, and R. Boukhanouf, "An experimental investigation on the effect of ferrofluids on the efficiency of novel parabolic trough solar collector under laminar flow conditions," Heat Transfer Eng. **40**, 753–761 (2016).
[10] M. Turkyilmazoglu, "Single phase nanofluids in fluid mechanics and their hydrodynamic linear stability analysis," Comput. Methods Programs Biomed. **187**, 105171 (2020).
[11] M. Turkyilmazoglu, "Nanoliquid film flow due to a moving substrate and heat transfer," Eur. Phys. J. Plus **135**, 781 (2020).
[12] M. Turkyilmazoglu, "On the transparent effects of Buongiorno nanofluid model on heat and mass transfer," Eur. Phys. J. Plus **136**, 376 (2021).
[13] F. A. Essa, A. H. Elsheikh, A. A. Algazzar, R. Sathyamurthy, M. K. Ahmed Ali, M. A. Elaziz, and K. H. Salman, "Eco-friendly coffee-based colloid for performance augmentation of solar stills," Process Saf. Environ. Prot. **136**, 259–267 (2020).

[14]A. Kosinska, B. V. Balakin, and P. Kosinski, "Theoretical analysis of erosion in elbows due to flows with nano-and micro-size particles," Powder Technol. **364**, 484–493 (2020).
[15]S. M. Shinde, D. M. Kawadekar, P. A. Patil, and V. K. Bhojwani, "Analysis of micro and nano particle erosion by the numerical method at different pipe bends and radius of curvature," Int. J. Ambient Energy (published online).
[16]A. M. Rashidi, M. Paknezhad, M. R. Mohamadi-Ochmoushi, and M. Moshrefi-Torbati, "Comparison of erosion, corrosion and erosion–corrosion of carbon steel in fluid containing micro-and nanosize particles," Tribol.-Mater., Surf. Interfaces **7**, 114–121 (2013).
[17]J. E. Minardi and H. N. Chuang, "Performance of a black liquid flat-plate solar collector," Solar Energy **17**, 179–183 (1975).
[18]M. Alberghini, M. Morciano, L. Bergarnasco, M. Fasano, L. Lavagna, G. Humbert, E. Sani, M. Pavese, E. Chiavazzo, and P. Asinari, "Coffee-based colloids for direct solar absorption," Sci. Rep. **9**, 4701 (2019).
[19]S. M. S. Hosseini and M. Mirzaei, "Assessment of the colloidal montmorillonite dispersion as a low-cost and eco-friendly nanofluid for improving thermal performance of plate heat exchanger," SN Appl. Sci. **2**, 1719 (2020).
[20]J. Awua, S. Ibrahim, and A. Kwaghger, "Investigation of thermal conductivity of palm kernel fibre nanofluid using de-ionized water and ethylene glycol mixed at ratio of 50:50 and 60:40," Int. J. Eng. Trends Technol. **49**, 47–53 (2017).
[21]R. Ranjbarzadeh, A. Moradikazerouni, R. Bakhtiari, A. Asadi, and M. Afrand, "An experimental study on stability and thermal conductivity of water/silica nanofluid: Eco-friendly production of nanoparticle," J. Cleaner Prod. **206**, 1089–1100 (2019).
[22]E. T. Ulset, P. Kosinski, Y. Zabednova, O. V. Zhdaneev, P. G. Struchalin, and B. V. Balakin, "Photothermal boiling in aqueous nanofluids," Nano Energy **50**, 339–346 (2018).
[23]E. T. Ulset, P. Kosinski, and B. V. Balakin, "Solar steam in an aqueous carbon black nanofluid," Appl. Therm. Eng. **137**, 62–65 (2018).
[24]R. Bardsgard, D. M. Kuzmenkov, P. Kosinski, and B. V. Balakin, "Eulerian CFD model of direct absorption solar collector with nanofluid," J. Renewable Sustainable Energy **12**, 033701 (2020).
[25]H. C. Jin, G. P. Lin, L. Z. Bai, M. Amjad, E. P. Bandarra, and D. S. Wen, "Photothermal conversion efficiency of nanofluids: An experimental and numerical study," Solar Energy **139**, 278–289 (2019).
[26]E. T. Ulset, "Utilizing solar vapour energy by use of nanofluids in a direct absorption solar collector," M.S. thesis, University of Bergen, 2018.
[27]P. G. Struchalin, H. Thon, D. M. Kuzmenkov, K. V. Kutsenko, P. Kosinski, and B. V. Balakin, "Solar steam generation enabled by iron oxide nanoparticles: Prototype experiments and theoretical model," Int. J. Heat Mass Transfer **158**, 119987 (2018).
[28]Y. Hwang, J. K. Lee, C. H. Lee, Y. M. Yung, S. I. Cheong, C. G. Lee, B. C. Ku, and S. P. Jang, "Stability and thermal conductivity characteristics of nanofluids," Thermochim. Acta **455**, 70–74 (2012).
[29]K. Leong, H. Mohd Nurfadhillah, S. Mohd, and N. Amer, "The effect of surfactant on stability and thermal conductivity of carbon nanotube based nanofluids," Therm. Sci. **20**, 429–436 (2016).
[30]Y. Hwang, J.-K. Lee, J.-K. Lee, Y.-M. Jeong, S.-i. Cheong, Y.-C. Ahn, and S. H. Kim, "Production and dispersion stability of nanoparticles in nanofluids," Powder Technol. **186**, 145–153 (2008).
[31]R. Rastogi, R. Kaushal, S. K. Tripathi, A. L. Sharma, I. Kaur, and L. M. Bharadwaj, "Production and dispersion stability of nanoparticles in nanofluids," J. Colloid Interface Sci. **328**, 421–428 (2008).
[32]C. F. Bohren and D. R. Huffman, *Absorption and Scattering of Light by Small Particles* (John Wiley & Sons, 2008).
[33]G. M. Hale and M. R. Querry, "Optical constants of water in the 200-nm to 200-μm wavelength region," Appl. Opt. **12**, 555–563 (1973).
[34]M. Du and G. H. Tang, "Plasmonic nanofluids based on gold nanorods/nanoellipsoids/nanosheets for solar energy harvesting," Solar Energy **137**, 393–400 (2016).
[35]R. A. Taylor, P. E. Phelan, T. P. Otanicar, R. Adrian, and R. Prasher, "Nanofluid optical property characterization: Towards efficient direct absorption solar collectors," Nanoscale Res. Lett. **6**, 225 (2011).
[36]W. L. McCabe, *Unit Operations of Chemical Engineering*, 7th ed. (McGraw-Hill Higher Education, 2005).
[37]W. Rohsenow, J. Hartnett, and Y. Cho, *Handbook of Heat Transfer*, 3rd ed. (McGraw-Hill Education, 1998).
[38]B. J. Lee, K. Park, T. Walsh, and L. Xu, "Radiative heat transfer analysis in plasmonic nanofluids for direct solar thermal absorption," J. Sol. Energy Eng. **134**, 021009 (2012).
[39]T. P. Otanicar, P. E. Phelan, R. S. Prasher, G. Rosengarten, and R. A. Taylor, "Nanofluid optical property characterization: Towards efficient direct absorption solar collectors," J. Renewable Sustainable Energy **2**, 033102 (2010).
[40]S. Parvin, R. Nasrin, and M. A. Alim, "Heat transfer and entropy generation through nanofluid filled direct absorption solar collector," Int. J. Heat Mass Transfer **71**, 386–395 (2014).