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Bionic structure mimicking frog eggs as working fluid for solar thermal collection

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ABSTRACT

The structure of frog eggs in the nature has inspiration for the designing of working fluids for solar thermal collection. This work explore the application of bionic structure mimicking frog eggs (BSMFE) as working fluid for solar photo-thermal conversion. According to the comparative experiments with Cu, CuO and carbon black nanofluids, it is found that the sustainability of suspension and photo-thermal conversion performance of BSMFE are better than those of other nanofluids, and BSMFE can achieve a higher heating rate in a short time. The performance of BSMFE-2 prepared from collagen protein and carbon black nanoparticles is better than that of BSMFE-1 prepared from bone glue and carbon black nanoparticles. This work provides an efficient but economical approach for industrial solar thermal collection.

1. Introduction

In solar thermal collection, working fluid is the key for the efficiency of photo-thermal conversion [1,2]. Nanofluids have high optical and thermal conversion efficiency [3,4]. As a result, nanofluids are becoming more and more widely used in solar thermal collection recently. Efforts have been done in the application of nanofluids in solar thermal collection [5–9]. Turkyilmazoglu [10,11] has made a detailed analysis of heat transfer in nanofluids. Zeiny et al. [12] experimentally investigated the direct-absorption nanofluids for solar thermal collection, and they concluded that photo-thermal conversion efficiency can be well predicted mathematically based on the optical properties of the used nanofluids. However, the poor sustainability [13] and high cost of nanofluids [14] limit their large-scale applications in practice.

Besides the photo-thermal conversion efficiency of the nanomaterial itself, the sustainable suspension of the nanomaterial in the medium is also the critical factor that determines the solar-thermal collection performance of the working fluids. The phenomenon that exists in the nature may have great inspiration for the designing of nanofluids for solar-thermal collection, such as Frog eggs. The frog eggs in the water are wrapped in a transparent hydrophilic glial membrane (see Fig. 1). Such core-shell structure not only enables the sustainable suspension of the eggs near the surface of water [15], but also helps to gather heat efficiently from the sunlight to maintain the temperature needed for the hatching of each egg in their cluster [16]. That is, whether the eggs are in a dispersed or aggregated state would has little impact on their solar absorption. Such magical mechanism could be utilized for solar-thermal collection.

At present, there are work about nanofluids with core-shell structure for solar thermal collection [17]. Fan et al. [18] used graphene as the core and Sn@SiO2@Ag as the shell to enhance solar absorption and thermal conductivity of the nanofluid. Their results showed that the nanofluid with core-shell structure has better solar absorbance. However, their preparation process is complex and costly.

Wang et al. [19] proposed the application of Chinese ink as the working fluid in solar thermal collection for the first time. Through the experiment, it is found that, compared with reported Cu and CuO nanofluids, the Chinese ink shows a surprising effect on both the performance of photo-thermal conversion and suspension sustainability. Further studies on the mechanism of photo-thermal transformation of Chinese ink showed that the ink particle has a colloid core-shell-like structure, where the carbon black was wrapped by a shell of bone glue. In this structure, the carbon black core is determined for the conversion of solar irradiation into thermal energy, and the shell of bone glue plays a significant role on the prevention of the ink particles from aggregation and deposition. Such structure is similar to that of frog egg. Therefore the structure of frog egg could be adopted to upgrade the nanofluid for solar-thermal collection from raw carbon black and collagen protein instead of Chinese ink.

In this work, a new working nanofluid with a bionic structure mimicking frog eggs (BSMFE) was prepared for solar-thermal collection. We first characterized the structure of BSMFE and then evaluated its

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Fig. 1. Frog eggs photos. The frog eggs are black in the left photo, and the eggs are being hatched into tadpoles in their cluster in the right photo.

suspension sustainability and performance of photo-thermal conversion. The aim of this work is to check the possibility of BSMFE as working nanofluids for solar photo-thermal collection.

2. Experimental

2.1. Materials and preparation of nanofluids

Inspired by the Chinese ink whose main components are carbon black and bone glue [20], we used high purity carbon black nanoparticles and bone glue to prepare a new working fluid, recorded as BSMFE-1. The carbon black nanoparticles were purchased from Tianjin Lihuajin Chemical Co. Ltd., and have an average diameter of 40 nm. The bone glue was purchased from Shijiazhuang Xu'ermei biological products factory, and its purity was 99%. The mass ratio of carbon black to bone glue is 1:2. In the preparation process, 0.1 g bone glue was first dissolved in 50 ml water by stirring, then 0.05 g bone glue was added into the solution, obtaining the BSMFE-1 solution with a carbon black content of 0.1 wt%. As the main component of bone glue is collagen protein, a sample is also prepared similarly with carbon black nanoparticles and collagen protein, and the ratio of carbon black to collagen protein was 1:2, obtaining the BSMFE-2 solution with a carbon black content of 0.1 wt%. The collagen protein was purchased from Bengbu Jingcheng Chemical Co. Ltd., and the purity of it was 99%. To note that this concentration is adequate for the nanofluids to approach their theoretical solar absorbance according to previous work [21–23] (Fig. 2).

Cu [24,25] and CuO [26,27] nanofluids have been found excellent in solar photo-thermal conversion in previous work. For comparison, Cu, CuO and carbon black nanofluids were also prepared by directly dissolving in pure water by fully stirring with a glass rod. The Cu and CuO nanoparticles were purchased from the Hongwu nanometer Marketing Center of Guangzhou Jiechuang Trade Co. Ltd., and had a purity of 99.99%. The average particle sizes of Cu and CuO were 100 nm and 30–50 nm, respectively. These obtained nanofluids also had a concentration of 0.1 wt%.

2.2. Characterization

The scanning electron microscope (SEM, Hitachi S-4700, Hitachi Company) and digital microscope (UM016, Mustech Electronics) were used to characterize the morphology particles in the carbon black, BSMFE-1 and BSMFE-2 samples after naturally volatilizing of water. In order to observe the interaction structure of collagen protein and carbon black in BSMFE, Coomassie Brilliant Blue (CBB) method was used to stain the protein in the carbon black, BSMFE-1 and BSMFE-2 samples. One milliliter CBB R-250 was added in 10 ml sample. After 10 min, the collagen protein in the solution was dyed blue, then they were observed with the digital microscope. The viscosities of the prepared working fluids were measured by rotational rheometer (ThermoFisher, Haake MARS 40) at a temperature of 20 °C.

Suspension sustainability of particles in the fluid is critical for the large-scale application of working fluid in solar thermal collection [28]. Lee et al. proposed a method to evaluate the dispersion stability of nanofluids [29]. In this work, however, the suspension sustainability of particle in the fluid was alternatively measured by spectrophotometer (PERSEE, T6), since absorbance is proportional to suspension density of the particles. Before measuring, the prepared working fluids including BSMFE-1, BSMFE-2, Cu, CuO and carbon black were placed standing and unmoved for 24 h, and the upper liquid was taken for the measurement of absorbance. The suspension sustainability are estimated as the closing degree of the absorbance of the upper liquid to the sample's initial state. Because the absorbance of sunlight has a form of ratio, not an absolute value, the selection of wavelength in the experiment will only affect the signal-to-noise ratio and accuracy. The measuring results are independent of the selected wavelength. Previous work of Povacz shows that the solar absorbance of fluid with a small addition of carbon black particles is about 95% [23], which suggested that carbon black has extremely strong absorption of sunlight at all wavelengths. Therefore, we chose a wavelength of 650 nm for the measurement of absorbance with spectrophotometer.

The performance of photo-thermal conversion [30] refers to the ability of the working fluids to convert solar energy into heat. The platform for the solar photo-thermal conversion experiment was set up as shown in Fig. 3. The collecting tube was made of organic glass. Because the intensity of the sunlight is difficult to be artificially controlled, we alternatively carried out the experiments of photo-thermal conversion under solar simulators instead of in the sunlight outside. Full-spectrum solar simulators (OSRAM UV300W) were used to simulate the irradiation of sunlight. Four full-spectrum solar simulators were uniformly arranged. At both ends of the tube, two thermocouples (HUAHANW TH10R-EX) were used to monitor the temperature of the nanofluids online. The ambient temperature was 30 °C.

BSMFE-1, BSMFE-2, Cu, CuO and carbon black working fluids with a mass fraction of 0.1 wt% were added to the collector respectively. Then the tube was put under the solar simulator for two hours. The temperature of the working fluid was taken every minute. During the irradiation process, seven evenly distributed points were selected on the surface of the tube to measure the intensity of light. The measured results revealed that the light was distributed evenly on the surface of the tube, and the light intensity was 13,000 lx in average. After experiment for 120 min, the temperature of the fluid at different time was obtained.

3. Results and discussion

3.1. Microstructure and velocity

Fig. 4 shows the SEM images of particles in the carbon black, BSMFE-1 and BSMFE-2 samples after naturally volatilizing of water. It