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Effect of surfactants on the stability and solar thermal absorption characteristics of water-based nanofluids with multi-walled carbon nanotubes

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ABSTRACT

This paper reports the effect of various surfactants on the suspension stability and the solar thermal absorption characteristics of water-based nanofluids containing multi-walled carbon nanotubes (MWCNTs) that can be used as working fluids for volumetric solar thermal receivers. The water-based MWCNT nanofluids were prepared using a two-step method with four commonly used surfactants: sodium dodecylbenzenesulfonate (SDBS), cetyltrimethylammonium bromide (CTAB), sodium dodecyl sulfate (SDS), and Triton X-100 (TX-100). The stability of the four surfactant-treated nanofluids was analyzed for over a month with an in-house developed laser transmission system. The effect of temperature on the stability of the nanofluid/surfactant mixtures was also examined. In addition, to identify the absorption characteristics of the four nanofluids, the spectral extinction coefficients were measured using an UV–Vis–NIR spectrophotometer. The absorbed sunlight fraction was calculated using the measured spectral extinction coefficient, which enabled an evaluation of the absorption characteristics of the nanofluids. The MWCNT nanofluids were clearly shown to enhance the absorption rate of solar thermal energy. The suspension stability and the absorption characteristics were also strongly affected by the type of surfactant. Moreover, using the absorbed sunlight fraction and suspension-stability factor, we experimentally show the relation between the absorption characteristics and suspension stability in nanofluids.

1. Introduction

Traditional thermal receivers, including flat-plate and parabolic trough receivers, have been widely used to capture solar thermal energy. These receivers, also called surface-based solar thermal receivers, capture solar thermal energy using metal plates or tubes with selective coatings. The thermal energy captured by the receiver is then transferred to a working fluid [1]. However, surface-based solar thermal receivers have inherent limitations in efficiency due to the irreversibility associated with the heat exchange between the solar plates and the working fluid [1–4]. To overcome these challenges, the direct-absorption solar collector (DASC), which uses the concept of volumetric absorption, has been introduced to the field of solar thermal applications [3–18].

Instead of using metal plates or tubes with selective coatings, the DASC captures solar thermal energy directly in a working fluid volume that has a high extinction coefficient. Conventional working fluids such as water, ethylene glycol, and thermal oil cannot be efficiently used for direct absorption of solar thermal energy due to their low extinction coefficients. However, working fluids containing multi-walled carbon nanotubes (MWCNTs) are a viable alternative for the direct absorption of solar thermal energy [3,4,11,17] because the MWCNT nanofluids have not only high thermal absorption characteristics, but also high thermal conductivity [19–23].

Typically, investigators use surfactants to prepare MWCNT nanofluids in order to ensure that the light absorbing nanoparticles remain well-dispersed in the liquid. For instance, Bandyopadhyaya et al. [24] manufactured water-based MWCNT nanofluids using surfactants including sodium dodecyl sulfate (SDS), cetyltrimethylammonium chloride (CTAC), and gum arabic. They also reported on the suspension stability of nanofluids with various surfactants, using X-ray scattering with dry nanoparticles and cryogenic

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Nomenclature

D	diameter of multi-walled carbon nanotube [nm]
I	intensity of light after passing through the cuvette [W]
I_0	intensity of light before passing through the cuvette [W]
$I_{initial}$	initial intensity of light after passing through a cuvette [W]
F	absorbed sunlight fraction
l	path length [cm]
L	length of multi-walled carbon nanotube [μm]
T	transmittance

Greek symbols

ϕ	carbon nanotube volume fraction
ε	suspension-stability factor
λ	wavelength [nm]
σ	extinction coefficient [cm^{-1}]

Subscripts

air	air
NF	nanofluids
s	sample

transmission electron microscopy (Cryo-TEM) at or below -170 °C. Unfortunately, these methods cannot be used to measure the suspension stability of nanofluids at operating temperature conditions.

Wen et al. [25] employed sodium dodecylbenzene sulfonate (SDBS) in preparing water-based nanofluids with MWCNTs. They reported the aggregation of MWCNT nanofluids with SDBS when heated to temperatures between 60 °C and 70 °C. A satisfactory criterion for quantifying MWCNT nanofluids suspension stability does not exist in the current literature. Assael et al. [26] used three types of surfactants (hexadecyltrimethyl ammonium bromide [CTAB], NanoSperse AQ,[1] and SDS) to obtain MWCNT nanofluids with high suspension stability. They characterized the suspension stability of the nanofluids using scanning electron microscopy (SEM) and micro-Raman spectroscopy. However, SEM and micro-Raman were used to measure the size and morphology of nanoparticles by measuring dry nanoparticles, rather than nanofluids. Rastogi et al. [27] manufactured water-based MWCNT nanofluids with surfactants such as Triton X-100 (TX-100), Tween 20, Tween 80, and SDS. However, they reported absorption characteristics using UltraViolet–Visible (UV–Vis) spectroscopy results for only the initial condition (soon after preparation), rather than the absorption characteristics over time.

Although much of the past research with MWCNT nanofluids has been done with surfactants resulting in good suspension stability, there is no systematic research that examines both suspension stability over time and the extinction coefficient. Therefore, this paper systematically reports the effect of surfactants on both suspension stability and the extinction coefficient of water-based MWCNT nanofluids over time. In addition, the effect of temperature on the stability of the nanofluids is examined. The results clearly show that suspension stability and absorption characteristics are strongly affected by the type of surfactant used with the base fluid. The present study shows that water-based MWCNT nanofluids produced with SDBS have a high extinction coefficient as well as high suspension stability between 10 °C and 85 °C, suggesting that SDBS is a superior surfactant for use in DASC.

2. Experimental study

2.1. Manufacturing processes of MWCNT nanofluids

Four commercial surfactants (SDBS, CTAB, SDS, TX-100) were used along with commercial MWCNT nanoparticles (D = 20 nm, L = 1–25 μm) to manufacture the water-based MWCNT nanofluids of this study. The water-based MWCNT nanofluids were produced using the two-step method with a wet-milling process. In the first step, the amount of each surfactant needed to produce a 0.2% surfactant mass fraction with de-ionized (DI) water was determined. All of the nanofluids had a surfactant mass fraction of 0.2%. Limiting the mass of surfactant in the nanofluid helped to limit the degradation of the thermal conductivity of the nanofluid as caused by the addition of the surfactant. In the second step, the MWCNT powder was milled with DI water using a planetary mill with a 1 mm zirconia ball for 60 min at 600 rpm (rpm). The MWCNT and the mixture of DI water and surfactant at 0.2% mass fraction were homogenized with a bath-type sonicator and mechanical stirrer at 200 rpm for approximately 1 h. Fig. 1 shows the appearance of the water-based nanofluids with MWCNT volume fraction ϕ = 0.0005%, ϕ = 0.002%, manufactured with different surfactants. As shown in Fig. 1, it is difficult for the unaided eye, transmission electron microscopy (TEM), scanning electron microscopy (SEM), and so on, to determine whether or not the nanofluids have high suspension stability. Consequently, in this study, a laser-scattering method is used to evaluate quantitatively the long-term suspension stability [28].

2.2. Suspension characterization of nanofluids

In this study, the intensity of light transmission (I) through each nanofluid was measured using an in-house developed laser transmission apparatus, as shown in Fig. 2 [28]. This was done to quantitatively evaluate the suspension stability of the nanofluids over the period of approximately one month. The suspension-stability factor, $\varepsilon(t)$, quantitatively indicates the degree of suspension stability, as given by [28]:

$$\varepsilon(t) = \frac{I_0 - I(t)}{I_0 - I_{initial}} = \frac{\Delta I(t)}{\Delta I_{initial}}, \quad (1)$$

where $I(t)$, I_0, and I_{initial} are the intensity of the light transmission through the cuvette and the nanofluid as a function of time, the intensity of the light incident to the cuvette, and the initial intensity of light transmission through the nanofluid and cuvette, respectively. The I_{initial} is assumed to represent the best dispersion immediately after sonication of the nanofluid. Values of the suspension stability factor can be from zero to 1. Smaller values of $\varepsilon(t)$ represent a larger degradation in the stability of the nanofluid suspension. The uncertainty of the $\varepsilon(t)$ measurement was ±5% of the measurement for a 95% confidence level. All measurement uncertainties are reported at the 95% confidence level.

2.3. Extinction coefficient and absorbed sunlight fraction

Typically, the extinction coefficient is obtained from either an absolute single-beam measurement technique or a differential

[1] Certain trade names and company products are mentioned in the text or identified in an illustration in order to adequately specify the experimental procedure and equipment used. In no case does such an identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.