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Carbon-nanotube-based liquids: a new class of nanomaterials and their applications

Ngoc Minh Phan[1,2], **Hung Thang Bui**[2], **Manh Hong Nguyen**[1] **and Hong Khoi Phan**[1]

[1] Center for High Technology Development (HTD), Vietnam Academy of Science and Technology, 18 Hoang Quoc Viet Street, Cau Giay District, Hanoi, Vietnam
[2] Institute of Materials Science (IMS), Vietnam Academy of Science and Technology, 18 Hoang Quoc Viet Street, Cau Giay District, Hanoi, Vietnam

E-mail: pnminh@vast.ac.vn and phkhoi@ims.vast.ac.vn

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Abstract

Carbon-nanotube-based liquids—a new class of nanomaterials—have shown many interesting properties and distinctive features offering unprecedented potential for many applications. This paper summarizes the recent progress on the study of the preparation, characterization and properties of carbon-nanotube-based liquids including so-called nanofluids, nanolubricants and different kinds of nanosolutions containing multi-walled carbon nanotubes/single-walled carbon nanotubes/graphene. A broad range of current and future applications of these nanomaterials in the fields of energy saving, power electronic and optoelectronic devices, biotechnology and agriculture are presented. The paper also identifies challenges and opportunities for future research.

Keywords: carbon nanotubes, liquids, nanomaterials, nanofluids, nanolubricants
Classification numbers: 5.11, 5.14

1. Introduction

Carbon nanotubes (CNTs) have attracted much attention because of their unique structure and remarkable mechanical, thermal and electrical properties [1–4]. CNTs have been used as additives in liquids to increase the thermal conductivity, one of the most important issues in industry [5]. Owing to their very high thermal conductivity (2000 $W\,m^{-1}\,K^{-1}$ compared to thermal conductivity 419 $W\,m^{-1}\,K^{-1}$ of Ag) [6], CNTs are one of the most suitable nanoadditives to fabricate the following nanomaterials: (i) 'nanofluids' for thermal dissipation in many industrial and consumer products; (ii) nanolubricants for improving the heat transfer, increasing the viscosity and therefore conferring to the lubricants the needed functions applied to various metallurgical contexts. These nanolubricants offer excellent characteristics in aspects of reducing friction coefficient, reducing wear effect of mating parts, self-repairing of minute damages caused by friction, and consequently result in longer life of engines, gear boxes, etc, lower consumption of fuel, better heat transfer and lower emission of waste gases; and (iii) nanosolutions affecting seed germination and seedling growth of plants cultured *in vitro* conditions, increasing the yield of plant cell biomass, and reducing the growth time.

In the present paper we review the latest results of experimental research on the fabrication and perspective applications of this new class of nanomaterials: nanofluids, nanolubricants and nanosolutions.

2. CNTs-based liquids for heat dissipation in microprocessors and high power light emitting diode (LED)

We develop an experimental setup to utilize a CNT-based liquid in a cooling system for microprocessors of the computer. Figure 1 is a schematic view of the thermal dissipation system for a computer processor using the CNT-based liquid [7].

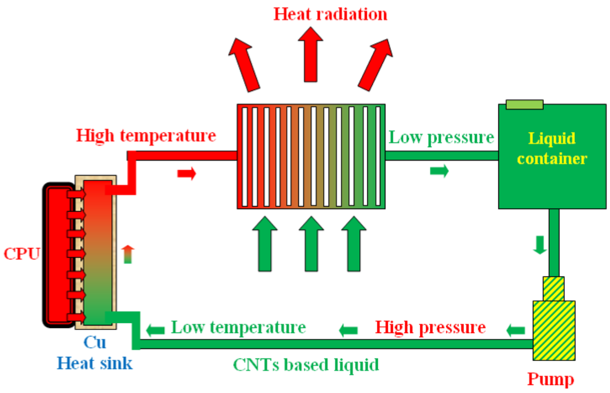

Figure 1. Scheme of the cooling system for CPU using the CNT-based liquid [7].

Multi-walled carbon nanotubes (MWCNTs) were produced at the Institute of Materials Science (IMS) using the thermal chemical vapor deposition (CVD) technique on a solid catalyst in a gas mixture of acetylene, hydrogen and nitrogen. The diameter and length of the grown MWCNTs were in the range 15–90 nm and several tens of μm, respectively [8]. The MWCNTs were then functionalized with the COOH functional group using the hemical oxidation method [9]. In order to disperse the MWCNTs–COOH in liquid with a concentration of 0.2–1.2 g l^{-1}, we used the Tween-80 surfactant and ultrasonic vibration treatment in 30 min [7]. According to the experimental results of Hilding *et al* [10], 30 min of the ultrasonication treatment is good enough to reduce the length of MWCNTs.

In figure 1, the copper substrate was set to directly contact with a central processing unit (CPU), the tracks inside the copper substrate were fabricated to allow fluid flows through it and absorb heat from the CPU. The CNT-based liquid was pumped into the Cu substrate with 2 cm^3 s^{-1} of flow-rate. The volume of the liquid tank was 500 ml. The testing computer was kept at 15 °C for all measurements. The thermal dissipation efficiency and thermal response of the system were evaluated by directly measuring the temperature of the CPU using a dedicated software and a built-in temperature sensor inside the CPU.

We chose a personal computer with the following configuration: Intel Pentium IV, 3.066 GHz, 512 MRAM, 80 GB Hard-disk and Window XP Service Pack 2 operating system for the measurement. The temperature of the CPU was measured by using Speed Fan 4.3.3 software and the CPU was pushed to operate in full load (100% usage of the processor) by using Stress Prime 2004 ORTHOS software [7].

The experimental results showed that when using a cooling fan, the temperature of the CPU was 20 °C at initial time, and then the temperature of the CPU was saturated at approximately 50 °C after 100 s working time. When using distilled water and the MWCNTs–COOH/distilled water for thermal dissipation, the temperature of the CPU was about 15–18 °C at initial time. The saturated temperature of the CPU reached 35, 30 and 28 °C when using distilled water, 0.6 g MWCNTs–COOH per liter distilled water and 1 g MWCNTs–COOH per liter distilled water after 30 min of working time, respectively. These results indicated that in comparison with the case of using the cooling fan, the saturated temperature of the processor decreased by 15–22 °C, and increasing temperature time was prolonged from 100 s to 30 min. By mixing CNTs–COOH (1 g l^{-1}) in the distilled water, the saturated temperature of CPU decreased by 7 °C compared to distilled water.

To evaluate the thermal dissipation efficiency in the CPU, we proposed a calculation model. In this model, heat-flow from the CPU to the liquid and from the coolant to the environment can be given by the following expressions:

$$I_1 = \frac{T_3 - \frac{T_1+T_2}{2}}{R_2}, \quad I_2 = \frac{\frac{T_1+T_2}{2} - T_0}{R_1}, \tag{1}$$

where T_0 (°C) is the temperature of environment, T_1 (°C) is the temperature of liquid flowing to the Cu substrate, T_2 (°C) is the temperature of the liquid flowing out of the Cu substrate, T_3 (°C) is the temperature of CPU, R_1 is the heat resistance between the CPU and the liquid (K/W) and R_2 is the heat resistance between the liquid and the environment (K/W). When liquid flowed through the copper substrate, the heat-flow can be expressed by

$$J = \frac{mC\,(T_2 - T_1)}{t} = \mathrm{FDC}\,(T_2 - T_1). \tag{2}$$

When the thermal dissipation process reached the saturation state, we have

$$P = I_1 = J = I_2, \tag{3}$$

where $C\,(\mathrm{J\,kg^{-1}\,K^{-1}})$ is the specific heat capacity of the liquid, $D(\mathrm{kg\,m^{-3}})$ is the density of the liquid, $F(\mathrm{m^3\,s^{-1}})$ is the flow-rate of the liquid, $P\,(\mathrm{W})$ is the heat-generating power of the CPU, I_1 (W) is the heat-flow from the CPU to the liquid, I_2 (W) is the heat-flow from the liquid to the environment (W) and $J\,(\mathrm{W})$ is the heat-flow in the liquid.

In our experiment the flow-rate of the liquid in the thermal dissipation system was kept at 2 cm^3 s^{-1}, the specific heat capacity and density of distilled water are 4185.5 J kg^{-1} K^{-1} and 999.97 kg m^{-3}, respectively. When using distilled water, $T_0 = 15$ °C, $T_1 = 20$ °C, $T_2 = 27$ °C and $T_3 = 35$ °C. From equations (2) and (3), the heat-generating power of the CPU is

$$P = \mathrm{VDC}\,(T_2 - T_1) = 58.6\ \mathrm{W}. \tag{4}$$

From equations (1), (3) and (4), the heat resistance between the CPU and the distilled water, and the heat resistance between the distilled water and the environment are, respectively

$$R_1 = \frac{\frac{T_1+T_2}{2} - T_0}{P} = 0.145\ \mathrm{K\,W^{-1}}, \qquad R_2 = \frac{T_3 - \frac{T_1+T_2}{2}}{P} = 0.196\ \mathrm{K\,W^{-1}}. \tag{5}$$

When using 1 g of CNTs–COOH per liter distilled water, $T_0 = 15$ °C, $T_1 = 18.5$ °C, $T_2 = 25$ °C and $T_3 = 28$ °C, the heat resistance between the CPU to the liquid and between the liquid to the environment are, respectively,

$$R_1 = \frac{\frac{T_1+T_2}{2} - T_0}{P} = 0.115\ \mathrm{K\,W^{-1}}, \qquad R_2 = \frac{T_3 - \frac{T_1+T_2}{2}}{P} = 0.107\ \mathrm{K\,W^{-1}}. \tag{6}$$

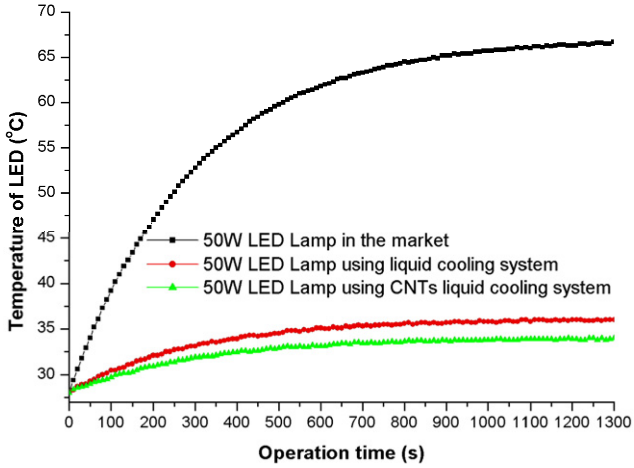

Figure 2. The temperature of the 50 W LED floodlight measured as a function of operation time in the following cases: without using the liquid cooling system, using distilled water in the liquid cooling system and using CNTs/distilled water in the liquid cooling system.

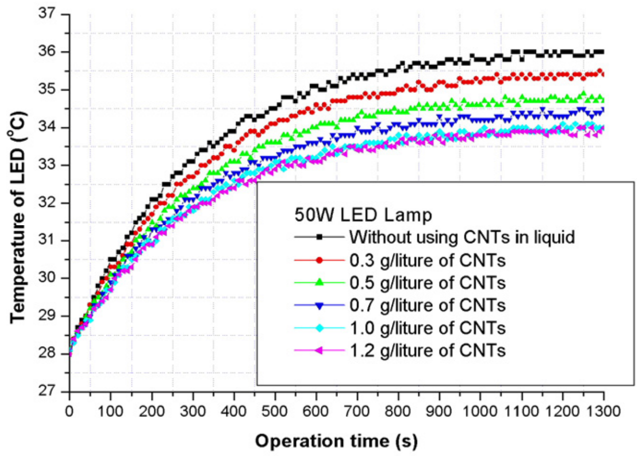

Figure 3. The temperature of the 50 W LED floodlight measured as a function of operation time with different concentrations of CNTs in distilled water.

In the case of using 1 g of CNTs–COOH per liter distilled water, the heat-generating power of the CPU can be expressed by

$$P = \mathrm{VDC}_{\mathrm{CNTs-COOH/H_2O}}(T_2 - T_1). \tag{7}$$

Using $P = 58.6$ W from equation (4) and formula (7), we obtained the following value of the specific heat capacity of the CNTs–COOH/distilled water:

$$C_{\mathrm{CNTs-COOH/H_2O}} = \frac{P}{\mathrm{VD}\,(T_2 - T_1)} = 4490\,(\mathrm{J\,kg^{-1}\,K^{-1}}). \tag{8}$$

The theoretical results showed that the presence of MWCNTs reduces the heat resistance of the thermal dissipation system, and increases the specific heat capacity of water from 4185.5 to 4490 J $\mathrm{kg^{-1}\,K^{-1}}$. The theoretical calculation using a heat dissipation model is described in detail in [7].

Initial results were also obtained in other experiments with the use of an appropriate MWCNT-based liquid cooling configuration for heat dissipation of high power LED lights. In this system, the copper heat-sink was also set to directly contact with the LED chip. The pump power consumption of the cooling system was 1.8 W. The dimension and power consumption of the fan were $120 \times 120 \times 38\,\mathrm{mm^3}$ and 3.6 W, respectively. The heat radiator was made with aluminum material, and dimensions of the heat radiator were $150 \times 120 \times 25\,\mathrm{mm^3}$, respectively. The environmental temperature was kept at 20 °C for all measurements by using an air conditioner. The temperature of the LED chip was directly measured by using an attached temperature sensor and WH7016E Electronic Digital Temperature Controller.

Figure 2 shows the temperature of the LED lamp (50 W) as a function of operation time in the following cases: without using the liquid cooling system, using distilled water in the liquid cooling system and using CNTs/distilled water in the liquid cooling system. In the case of not using the liquid cooling system, the saturation temperature of the LED chip reached 66 °C. In the case using distilled water or CNTs/distilled water in the liquid cooling system, the saturation temperature of the LED chip reached 34–36 °C, reduced by about 30 °C compared to the case of not using the liquid cooling system. It can also be seen from figure 3 that the temperature of the LED lamp is drastically reduced by about 2.5 °C by using the CNT-based liquid with a 1 g CNTs per liter distilled water concentration.

Our experimental and calculation results confirm the advantage of CNTs as an excellent additive component in liquids for the thermal dissipation media of high power electronic and optoelectronic devices.

3. CNT-based nanolubricants and their applications in industry

The nanotechnology involved in the lubrication using nanomaterial additives, such as chemically stable metals (e.g. nikel and copper) [11], metal oxides (e.g. CuO and TiO_2) [12, 13], metal sulfur (e.g. WS_2 and MoS_2) [14] carbon in various forms (e.g. diamond, graphite, carbon nanotubes, fullerene and graphene) [15–18], and so on is a rapidly developing scientific area and has been watched with interest for the past 10 years.

Among the above-mentioned nanoadditives, CNTs are considered as excellent candidates for improving properties of lubricants, which promise many applications in industry. Although CNTs have good dispersibility in mineral oil but agglomeration of the CNTs occurs within no time. In order to obtain a stable lubricant, one can either use a surfactant or mix CNTs to the mineral oil using ultrasonication. Ehsan-o-llah *et al* [19] studied the effect of MWCNTs in different concentrations on the properties of engine oils. Among the different methods, which have been applied for dispersing nanotubes inside the base oil, the functionalization method for CNTs and using a planetary ball mill have been determined as the best methods for stabilization of nanotubes inside the SAE 20 W50 engine oil. According to the obtained results of their study, the thermal conductivity and kinematic viscosity of MWCNT-based nanolubricants with respect to the base oil, as can be seen in figures 4 and 5, are improved considerably. Bhaumik and Prabhu have obtained a stable lubricant for a long time using ultrasonication without the help

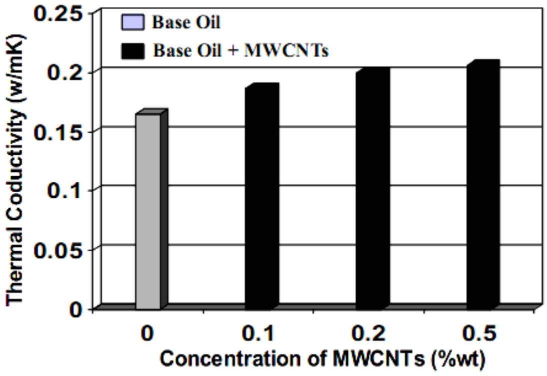

Figure 4. Thermal conductivity of MWCNT-based nanolubricants [19]. Reprinted from Ehsan-o-llah *et al* [19]. © 2013, with permission from Elsevier.

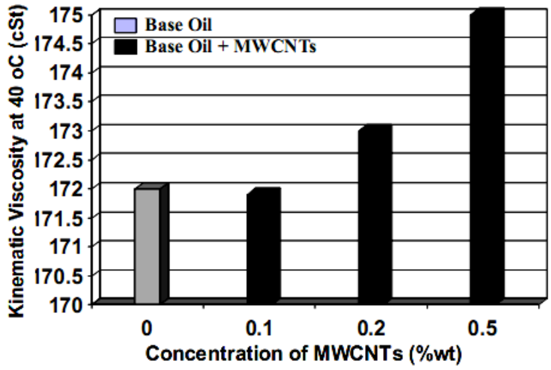

Figure 5. Kinematic viscosity of MWCNT-based nanolubricants at 40 °C [19]. Reprinted from Ehsan-o-llah *et al* [19]. © 2013, with permission from Elsevier.

Figure 6. MWCNT-based nanolubricants fabricated at IMS.

of a surfactant [20]. Ultrasonication is the process in which the length of CNTs is broken to increase the ease of dispersion of CNTs in oil and hence maintains stability for a long time.

As an example, in figure 6 we present our specimens of MWCNT-based nanolubricants fabricated at IMS using the ultrasonication method mentioned above. The specimens with various MWCNT concentrations dispersed in mineral oil were stable up to several months. The research has shown that lubricating oils with CNT additives exhibit improved load-carrying capacity, anti-wear and friction-reduction properties.

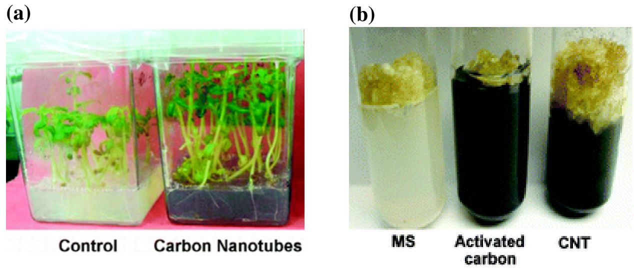

Figure 7. Tomato seeding 27 days old, growing *in vitro* on medium without and with MWCNTs (a), and MWCNTs induce growth enhancement of tobacco cells (b) [21, 23]. (a) Reprinted with permission from Khodakovskaya *et al* [21]. © 2009 American Chemical Society; (b) reprinted with permission from Khodakovskaya *et al* [23]. © 2012 American Chemical Society.

4. CNT-based solutions and their perspective applications in biotechnology and agriculture

In contrast to potential adverse health and environmental effects often announced in the news about nanotechnology, scientists in Arkansas have recently reported that the CNTs could have beneficial effects in agriculture. Their studies found that tomato seeds exposed to CNTs germinated faster and grew into larger, heavier seedlings than other seeds [21]. Khodakovskaya *et al* reported that their previous research demonstrated that the MWCNTs can penetrate through the thick coatings on seeds, stimulate germination of the seeds and stimulate the growth of certain plants. MWCNTs are wisps of pure carbon so small that thousands would fit on the period at the end of this sentence [22, 23]. These discoveries have the potential to transform agricultural practices in the near future and to provide solutions to some of the most serious problems related to plant growth and development.

The scientists have found that tiny amounts of MWCNTs still enhance the activity of genes involved in cell growth. MWCNTs also seem to work by activation of channels that transport water into cells, helping cells to divide and to grow faster. However, more research should focus on how MWCNTs affect the growth of plant cells of many other plant species, grown in large industrial vats, which find extensive use in producing medical and commercial products and plants for agriculture (see figure 7).

5. Conclusions

It is clearly seen that CNT-based liquids have opened up many unique applications in heat dissipation for electronic devices such as CPU or LED, nanolubricants for engines and nanosolutions for biotechnology and agriculture. It is expected that CNT-based liquids can be widely used in the near future.

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