06

Thermal conductivity of nanofluids modified with hybrid nanomaterial of detonation diamond nanoparticles-carbon nanotubes composition

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Received October 4, 2024
Revised October 4, 2024
Accepted October 4, 2024

Nanofluids based on a hybrid carbon nanomaterial consisting of individual formations, the central part of which is a diamond nanoparticle, and the peripheral part is carbon nanotubes, have been studied. It has been shown that the factor determining the thermal conductivity coefficient of a nanofluid is the volume fraction that nanoparticles make up. This has been proven for spherically symmetric nanoparticles. Estimates show that this property will also manifest itself to some extent for nanoparticles of other shape.

Keywords: nanofluid, nanodiamond, carbon nanotube.

DOI: 10.61011/TP.2025.02.60824.298-24

Introduction

Effective heat removal systems are a mandatory component of most material processing techniques. Turning, milling, drilling, polishing, cutting of steels, cast irons, non-ferrous metals and alloys and non-metal structural materials, die forging and rolling are characterized by high static and dynamic loads, high temperatures, impact of workpieces on cutting tools, forging and rolling equipment. The main purpose of effective heat removal systems in these conditions is to reduce the temperature, processing power parameters and wear of cutting tools, dies and rolls. Furthermore, heat removal systems shall meet sanitary, environmental and other requirements, have a set of corrosion resistant, detergent, antibacterial and other operational properties. Heat removal systems used for material cutting and forming increase equipment performance, reduces scrap, improve labor conditions and reduce the number of process operations in some cases. To solve this problem, many researchers often use so-called nanoliquids — stable material suspensions with high thermal conductivity, in particular, based on detonation nanodiamonds [1] and carbon nanotubes [2]. Record-breaking thermal conductivity is the reason why these materials are so popular. Thus, thermal conductivity of detonation nanodiamonds is estimated in $2000\,\mathrm{W/(m\cdot K)}$ [3], and thermal conductivity of carbon nanotubes may reach up to $3000\,\mathrm{W/(m\cdot K)}$ [4].

Modification of heat removal systems based on nanoliquids with carbon hybrid nanomaterials composed of detonation diamond nanoparticles−carbon nanotubes (DND−CNT), as shown before in [5,6], provides unique heat removal systems that have cooling liquids with high thermal conductivity. Thus, the service life of machining tools and part processing rates will be improved, while the heat removal system properties and quality of processed materials will not be much impaired.

Production of cooling nanoliquids based on such carbon nanomaterials is an easy, repeatable and scalable process.

1. Thermal conductivity of nanoliquid with DND−CNT hybrid material

The key property of nanoliquid that is prepared by adding DND−CNT powder to the liquid (water, ethyleneglycol, transformer oils) is the thermal conductivity coefficient k_l that is much lower than that of the DND−CNT hybrid material k_p.

Concentration of the DND−CNT material used for experimental studies [5,6] are so low that particles don't interact with each other and each particle only affects thermal conductivity of that part of liquid that is around it.

Thus stated, the thermal conductivity coefficient of nanoliquid k_{eff} is generally determined using the known Maxwell equation (see, for example, [7,8]):

$$k_{\mathrm{eff}} = k_l \, \frac{k_p + 2k_l + 2(k_p - k_l)\varphi}{k_p + 2k_l - (k_p - k_l)\varphi}. \tag{1}$$

Besides the thermal conductivity coefficients, this ratio includes the volume fraction φ occupied by the hybrid material particles in the nanoliquid. Using the fact that in the given nanoliquids $k_p \gg k_l$, we find that the growth of the thermal conductivity coefficient of nanoliquid compared with the thermal conductivity coefficient of liquid without nanoparticles $K = k_{\mathrm{eff}}/k_l$ will be defined only by the volume

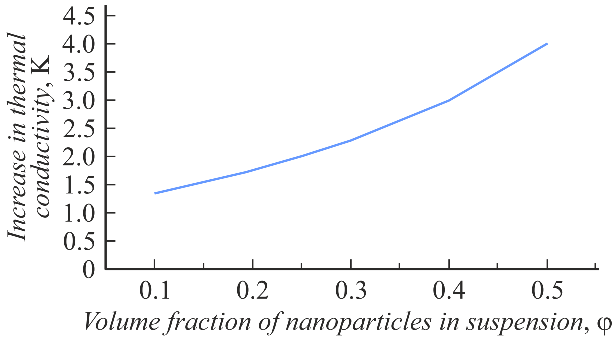

Figure 1. Increase in the thermal conductivity coefficient of nanoliquid compared with that of liquid without nanoparticles (K times) depending on the volume fraction φ occupied by the hybrid material particles in nanoliquid.

fraction φ. We have

$$K = \frac{1+2\varphi}{1-\varphi} \tag{2}$$

or

$$\varphi = 1 - \frac{3}{2+K}. \tag{3}$$

Curves used to determine the volume fraction of particles, for example, DND–CNT, to be added to the liquid with low thermal conductivity coefficient (water!) so that the thermal conductivity of the resulting nanoliquid is K times higher are shown in Figure 1.

High thermal conductivity of the nanoliquid with the DND–CNT hybrid material and capability to control its magnitude depend on the structure and shape taken by the DND–CNT hybrid material particle in the liquid.

2. Structure and shape of the DND–CNT hybrid material in the liquid

Figure 2 shows a scanning electron microscopy (SEM) image of a material [6], on the basis of which nanoliquid was prepared for the expected heat removal systems.

Figure 3 shows layout of this material. Up to the size equal to approx. 400 nm, the particle will be considered as spherically symmetric.

Material whose characteristics are described in [6,9] consists of multilayer (3 and more) CNTs with a lateral dimension of about 20 nm, length of at least 150 nm each, thermal conductivity coefficient of about 1000 W/(m · K),and the DND-aggregates have a size of about 50–100 nm and consist of the agglomerates of diamond nanoparticles with a size of about 20 nm that are formed by crystalline diamond nanoparticles with a size of about 4–5 nm. Thermal conductivity coefficient of DND is at least 1000 W/(m · K). The number of CNTs that are attached to each DND is unknown. Possible density of application of CNTs grown on a flat surface was studied in [10]. CNTs are usually distributed approximately uniformly and occupy about 10% of the

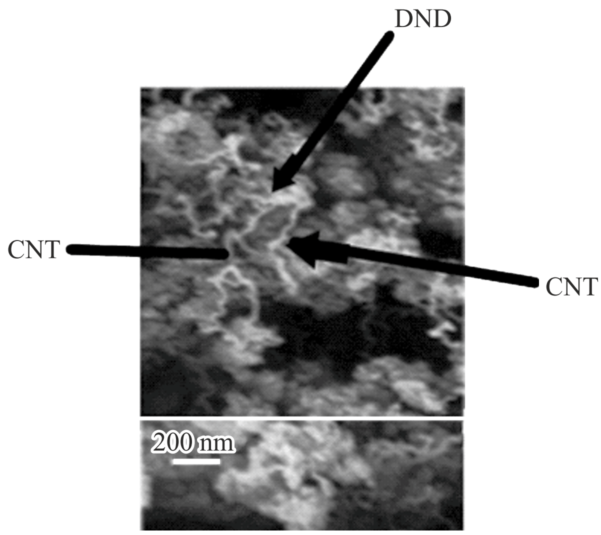

Figure 2. SEM of the DND–CNT hybrid material.. CNTs grown on the DND surface can be seen. Scale 200 nm.

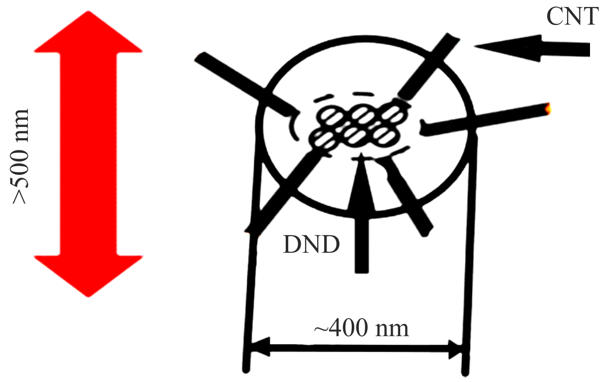

Figure 3. Layout of the DND–CNT hybrid material particle. CNT grown on the DND surface being a diamond nanoparticle agglomerate can be seen [6].

surface area. By transferring this result to the DND–CNT hybrid material, an individual DND–CNT particle will be represented as an object with almost spherical symmetry, in the center of which there is DND surrounded by straight-line CNT arrangement of which in turn do not break the symmetry that much. thermal conductivity coefficient of an individual DND–CNT material k_p is taken as at least 1000 W/(m · K).

3. Opportunity of creating effective heat removal systems

Dependence shown in Figure 1 is of general nature.

Figure 4 shows comparison of measurements described in [5] with calculations using equation (3). Compliance of the measurements with the calculations is obvious!

It turned out, that when the thermal conductivity coefficient of nanoparticle material significantly exceeds that of

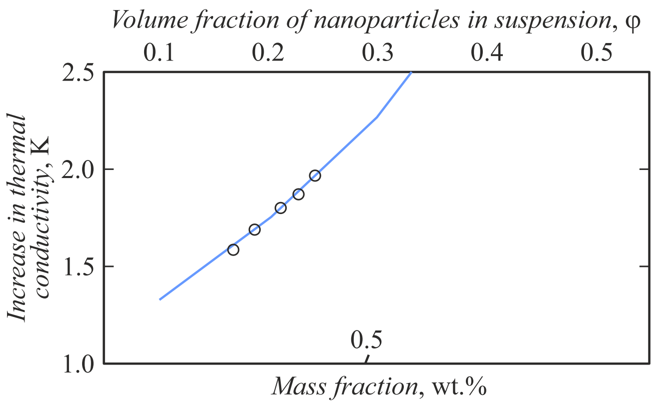

Figure 4. A pat of the curve shown in Figure 3. For the experiment, the DND–CNT hybrid material with a mass fraction of *m* was added to water at 50°C. Experimental data is shown by white dots. Solid line — calculation results using equation (3).

the liquid on the basis of which nanoliquid is prepared, the thermal conductivity coefficient itself of the additive material is not important. A volume fraction of nanoparticles is factor that defines the thermal conductivity coefficient of nanoliquid. This is proved in this work for spherically symmetric nanoparticles, but it appears that such property will be to a greater or lesser degree also demonstrated for nanoparticles with other shape.

Note that the particle size measurements by the dynamic light scattering (DLS) method gave a result equal to approx. 50 nm [6]. This suggests that the particle sizes measured by the DLS method probably cannot be considered as correct and applicable for investigating thermal properties of such porous particles. The DND–CNT particle appeared to have 10 times as large effective size for thermal effects compared with the size at which interaction between light and such particle appears in the DLS method.

In this context, the DND–CNT hybrid material is unparalleled. In the spherical layer where CNTs are located, the thermal conductivity coefficient will be lower than that of CNTs themselves, but it will be certainly still much higher than the thermal conductivity coefficient of the liquid used to prepare the heat-conducting nanoliquid. However, „heavy“ CNTs occupy only a small portion of the layer volume, which reduces the layer density significantly and leads to the fact that rather significant volume fractions correspond to very small mass fractions of hybrid nanoparticles. Other materials with such property are unknown to the authors.

Conclusions

The described properties of the DND–CNT material offer the opportunity to use a suitable nanoliquid in preparing unique effective heat removal systems with high thermal conductivity coefficient and small nanoparticle additives that usually impair viscous, sanitary, environmental, corrosion resistant and other properties.

Funding

This study was carried out as part of RSF project № 24-29-00252.

Conflict of interest

The authors declare no conflict of interest.

References

[1] F. Mashali, F. Alkhaldi, G. Mirshekari. Heat Transfer., **35** (6), 780 (2022). DOI: 10.1080/08916152.2021.1947418
[2] M. Moghaddari, F. Yousefi, S. Aparicio, S.M. Hosseini. J. Mol. Liq., **307**, 112977 (2020). DOI: 10.1016/j.molliq.2020.112977
[3] L.S. Sundar, M.J. Hortiguela, M.K. Singh, A.C. Sousa. Int. Commun. Heat Mass Transfer, **76**, 245 (2016). DOI: 10.1016/j.icheatmasstransfer.2016.05.025
[4] E. Pop, D. Mann, Q. Wang, K. Goodson, H. Dai. Nano Lett., **6**, 96 (2006). DOI: 10.1021/nl052145f
[5] A.A. Vozniakovskii, A.P. Voznyakovskii, S.V. Kidalov, E.K. Kalashnikova. IOP Conf. Ser. Mater. Sci. Eng., **1118** (1), 012024 (2020). DOI: 10.1088/1757-899X/1118/1/012024
[6] A.A. Vozniakovskii, T.S. Kol’tsova, A.P. Voznyakovskii, A.L. Kumskov, S.V. Kidalov. J. Colloid Interface Sci., **565**, 305 (2020).DOI: 10.1016/j.jcis.2020.01.034
[7] G. Carslaw, D. Eger, *Teploprovodnost tverdykh tel* (Nauka, M., 1964) (in Russian).
[8] L.D. Landau, E.M. Lifshits. *Gidrodinamika* (Nauka, M., 2003), vol. 50 (in Russian)
[9] A.E. Aleksenskiy, E.D. Eydelman, A.Ya. Vul’. Nanoscience Nanotechnology Lett., **3** (1), 68 (2011). DOI: 10.1166/nnl.2011.1122
[10] A.Ya. Vul’, K.V. Reich, E.D. Eidelman, M.L. Terranova, A. Ciorba, S. Orlanducci, V. Sessa, M. Rossi. Adv. Sci. Lett., **3** (2), 110 (2010). DOI: 10.1166/asl.2010.1104

Translated by E.Ilinskaya