International Communications in Heat and Mass Transfer 95 (2018) 147–154

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Water-based graphene quantum dots dispersion as a high-performance long-term stable nanofluid for two-phased closed thermosyphons

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ARTICLE INFO

Keywords:
Graphene quantum dots
Nanofluids
Heat transfer
Thermosyphon
Thermal performance

ABSTRACT

Water-based graphene quantum dots (GQD) suspension has great potential for different heat transfer applications as a novel coolant due to their unique colloidal stability, high thermal conductivity and low penalty for rheological properties once loading GQD. To this end, graphene quantum dots were firstly prepared through a new and cost-effective exfoliation procedure. Based on the morphological characterization, the average thickness and diameter of the synthesized amine treated-GQD (AGQD) were determined as mostly less than 1 nm and in the range of 5–20 nm, respectively. Case studies show that water-based AGQD nanofluid at very low weight fractions shows a considerably higher thermal conductivity than that of base fluid. In a detailed rheological investigation of the water-based AGQD nanofluid, no noteworthy increase was observed in comparison with the base fluid, which is considered as a major benefit for this novel generation of coolants. The water-based AGQD nanofluids were also found to be especially more effective in the thermosyphon in terms of overall thermal properties such as net heat transfer, and thermal efficiency, and rheological property such as effective viscosity, as well as, total pressure drop in comparison to the distilled water. Since the water-based AGQD nanofluids show no sedimentation, high thermal conductivity and fairly no effect on rheological properties, it would provide an economical approach for enhancing the performance of industrial heat pipes and thermosyphons.

1. Introduction

One of the important equipment in the electronics industry, thermal and electrical applications, is various kinds of heat pipes. Furthermore, heat pipes provide the advantage of energy-efficient vehicles with the minimal requirements for a long-term maintenance [1]. The properties of the apparatus such as the dimension, temperature of base fluid, heat flux, and working fluid are the key factors considered in designing heat pipes [2]. In this context, heat pipes can be divided into four main different groups: loop heat pipe, heat pipe with wick, thermosyphon heat pipe, and thermosyphon loop. Based on the heat transfer rate, the thermal yield, the installation reason, and the objective device to be cooled, different kinds of heat pipes are selected for a particular application [3].

Earlier reports demonstrated that the thermal performance of the thermosyphon heat pipe depends on different factors, including base fluids, right filling ratio to the evaporator volume, design, bend angle and bent position [4,5]. As the key essential issues to achieve an improvement in the performance of thermosyphons, different filling ratios, geometry, working fluids, diameters, bend angles, rotation and vibration systems have been investigated [6–10]. In spite of the fact that all innovations mentioned above resulted in a positive impact on the thermal performance of thermosyphon heat pipe, the most cost-effective factor may be the use of high thermally conductive working fluid, particularly for those systems that are already manufactured [11,12].

As mentioned previously, the thermal performance of the thermosyphon heat pipes is affected by working fluids and this subject has been studied comprehensively [13–17]. Moreover, earlier reports [18–20] confirmed that the thermal performance of the heat pipes is increased by using nanofluids. In a study by Choi [21], the addition of copper nanoparticles into the base fluids resulted in an enhancement in

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https://doi.org/10.1016/j.icheatmasstransfer.2018.05.009

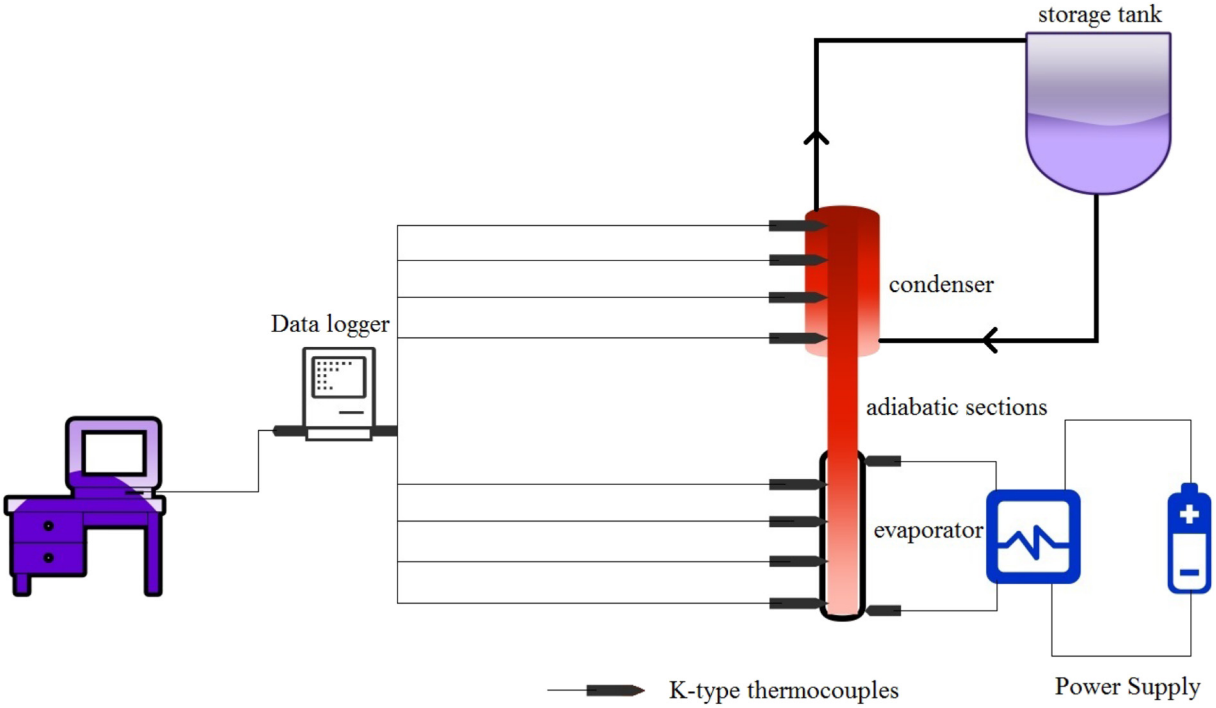

Fig. 1. Schematic of the experimental setup (TPCT).

thermal conductivity. In another study, Zeinali Heris et al. [22] studied the convective heat transfer coefficient of water-based CuO nanofluids and made a comparison with the results of water-based Al_2O_3 nanofluid. A higher convective heat transfer coefficient has been obtained for water-based Al_2O_3 nanofluids as compared to the water-based CuO nanofluids. In another approach, Shanbedi et al. [5] investigated the performance of a two-phase closed thermosyphon (TPCT) in the presence of multiwalled carbon nanotubes (MWCNT). They were observed ca. 11% increase in the thermal efficiency of the TPCT at 90 kW. In a study by Amiri et al. [1], a water-based GNP nanofluid was prepared in the presence of graphene nanoplatelets (GNP) and a rapid microwave-assisted procedure was used for covalent functionalization of GNPs with carboxylic groups to gain higher stability. According to the results, a significant enhancement in total performance of TPCT was achieved.

Despite all the promising properties of carbon nanostructures such as extremely high thermal conductivity and superior stability in the presence of covalently and non-covalently functionalization, they have one or two micro size dimensions. These micro dimensions may result in some failures such as erosion, chocking loops, etc. and they cannot be used in miniature thermosyphons. Alternatively, most of the metal and metal oxide nanoparticles with nanometer dimensions exhibit the difficulty of long-term stability. This problem is intensified by the lack of potential for performing covalent functionalization. So, introducing a carbon-based nanoparticle with the ability of covalent functionalization to solve the problem of colloidal stability and being in nanometer scale (in diameter and length) can be a solution herein. Fascinating properties of GQDs including fully nano-sized dimensions, high specific surface area [23], great stability in aqueous media [24] and promising thermophysical properties can be an excellent candidate to solve all the mentioned difficulties with the previous nanofluids. To investigate the effect of GQDs on the TPCT performance, in the present study, we synthesized the GQDs with a simple method based on covalent reactions. Due to the small size particles and the presence of covalently-functional groups, the colloidal stability of water-based GQDs was magnificent. The water-based GQDs samples were then characterized and the thermal performance in a thermosyphon was evaluated. The presented results showed that thermo-physical property of water-based GQDs nanofluids were outstanding as compared to the other nanofluids. Overall heat transfer, thermal efficiency, thermal resistance and pressure drop showed significant increases in the presence of water-based GQDs nanofluids even at a very low concentration.

2. Materials and methods

Herein, a modified Hummers method was employed to prepare the graphite oxide sheets from natural graphite powder [25]. In order to prepare GQDs, the method reported by Zhang et al. [25] with slight modification was used. Typically, 2.0 g of the graphite oxide were oxidized in the concentrated HNO_3 (60 mL, 38 wt%) and H_2SO_4 (180 mL, 98 wt%) for 48 h under mild ultrasonication. After cooling, the mixture was then diluted with 1200 mL of deionized water and subsequently was centrifuged at 4000 rpm to separate un-exfoliated material. The supernatant was then diluted with the deionized water. The colloidal suspension was then dialyzed using a dialysis bag (Mw cut off: 3500 *Da*) overnight.

To remove the acidic groups decorated on the edge of GQDs, 100 mL of colloidal solution was mixed with deionized water (100 mL) and ammonia solution (120 mL) in a vessel. The resulting black suspension was sonicated in a 300 W probe-sonicator for 30 min. The mixture was then stirred for 4 h at 100 °C. After cooling to room temperature, the resulting black suspension centrifuged at 25000 rpm and the supernatant was collected. Once performing the reaction step, a majority of oxidized GQDs changed to the amine-treated GQDs (A-GQDs). Finally, a rotary evaporator was used to concentrate the A-GQDs solution at 50 °C, following by drying in a vacuum oven to obtain the dried A-GQDs powder.

2.1. *Two-phase closed thermosyphons*

The schematic of the experimental apparatus applied in the present study is depicted in Fig. 1. The employed TPCT included a copper tube with the inner diameter of 20 mm and a length of 1000 mm, which provide three sections: the evaporator, the condenser, and the adiabatic section. The lengths of evaporator, condenser and adiabatic sections are