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Improvement of Heat Sink Performance Using Graphite and Graphene Coating

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Abstract

This experimental research depicts the role of coating hot surfaces by graphite and graphene on the process of heat dissipation from these hot surfaces. Three aluminum specimens have been prepared for test, one of theme is coated by graphite, another one by graphene a while the third is left free of coating for comparison purpose. Each specimen is tested separately in a home-made wind tunnel. A plate electrical heater is adhered on the bottom of the specimen to simulate the generated energy by a heat sink. A heat sink composed of high thermal conductivity was applied between the heater plate and the base plate of heat sink to reduce the contact resistance to heat flow. The experiments are conducted with four turbulent Reynolds number. The results reveal that the sample coated by graphene exhibits the best thermal dissipation while the uncoated specimen shows the worst thermal performance.

Keywords: Micro heat sink, Graphite-graphene coating, Turbulent Reynolds number, Wind tunnel.

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1. Introduction

The most challenges, nowadays, facing researchers is the thermal aspect of application workloads electronic devices such as used in smartphones which are associated with a plenty integrated circuit and operating for many hours, while the small size of such devices is demanded.

The dissipation of the generated heat in such devices is an important factor to increase its abilities especially in hardware, for this reason many researchers have focused on managing the generated heat in electronic components [1, 2].

In fact, the life and reliability of microelectronics are associated with the inverse of operation temperature of the equipment. Micro heat sink (MHS) is the device that removes heat from high temperature surfaces to the cooling fluid, and keeps the equipment temperature below the maximum permissible value [3]. To get rid of the heat better, and this is main aim of present work, it is mainly done by improving the surface of the heat sink, either by increasing the surface area or by coating the surface of the heat sink with materials that increase heat emission such as graphite and graphene. This strategy is not only improving the thermal conductivity, but also increases the heat exchanging area [4].

The composites based on graphene are emerging as a new materials class that hold promise for multi applications. Due to its unique structure, the graphene which a single sheet of graphite had extraordinary mechanical, thermal, and electrical properties [5, 6]. Graphite and Graphene is often thought to hold advantages over other materials in electronics cooling systems because of its higher thermal conductivity [2]. The thermal properties of graphite depend on its anisotropic structure. The conductivity in the strong bonding layers (in-plane) direction is generally 398 W/m.K and the orthogonal direction from the layers (through thickness) the conductivity is 2.2 W/m.K at a temperature at 25 °C. Graphite is also an electrically conductive material [7]. While the ballistic thermal conductance of graphene is isotropic [8] and it is about 3000 to 5000 W/m^2.K at room temperature [9]. A high thermal conductivity indicates a very good heat sink and a rise low temperature during the operation of the equipment [2].

Several studies have been proposed to deal with the enhancement of the heat dissipation potential of metal conventional heat dispersants by mechanically coated graphene nanoscale sheets [10-14]. Hence it is shown that nanoparticle of graphene can be one of the main components in electronics cooling sector due to the high enhancement in thermal property [15, 16]. However, one of the methods for coating to enhancement the thermal dissipation by insert various combinations of ceramic, as graphite, SiO2 or Al2O3, is the ultrasonic mechanical coating and armouring (UMCA) technique. With a suitable insertion of ceramic powders, the aluminum heat sink temperature could be lowered by 5-11°C, which is highly favorable for applications which requirement a cooling component [17]. Thermal conductivity of the composites (compressed expanded natural graphite, CENG, /Wood's alloy composite) can be 2.8–5.8 times than that of the Wood's alloy. On the other side, the ranges of the latent heat of the composites from 29.27 to 34.20 J/g. Due to the graphite is not subject to change in the phase, it is expected that the latent heat be linear with the amount of the alloy Wood. Composite materials have potential use in the heat sink into electronic devices [18].

Heat sinks made of natural graphite/epoxy compounds with light weight and high performance instead of the traditional designs of aluminum and copper. It was found on the hybrid heat sink optimized to have an almost thermal performance equivalent, nearly, to the performance of the heat sink copper with low weight by 40 % [19].

Additionally, the graphene coating accelerates the transmission of the internal heat in helicopter rotor and improving the de-icing and anti-icing efficiency of the helicopter rotor, heat radiation also plays a major role in enhancing the performance of heat dissipation which changes with thickness of graphene layer [20].

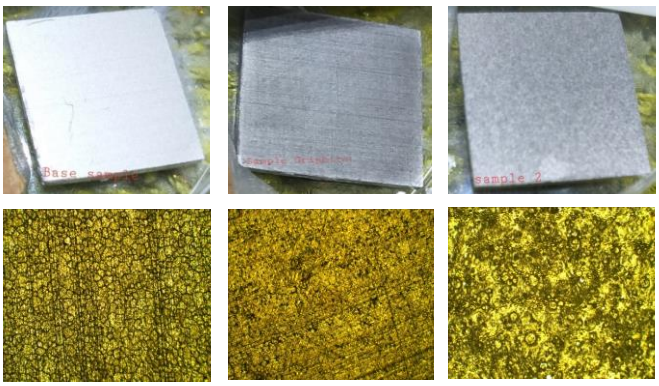
Based on the best author's knowledge, the impact of heat convection under various forced air velocities at surface-air boundary over coated surfaces with various layers of nano graphene or graphite still do not studied precisely. This research is intended to fill this gap by experimental study of the effect of coating aluminum samples by graphite once and by graphene at another time, and comparing their thermal performance with the uncoated sample. That is to find out the difference between the three models. The coating process is to be performed by using a remote-controlled chemical spray system to avoid risks of human health coming from graphene nanoparticles.

2. Preparing and Coating Figures and Tables

Three samples have been fabricated by aluminum 20 × 20 mm with 1 mm thickness. Then, cleaning the surfaces by ultrasonic cleaner (MTI corporation, USA) for 60 minutes, first and second samples covered with multilayer of graphene and graphite respectively.

Preparation of graphene solution was achieved by dispersing the graphene nanopowder (25 mg) and Sodium dodecyl sulphate (SDS, 1 %) in deionized water (DI, 40 ml) and sonificat the resultant solution experienced in bath sonification (60 minutes). After that, polyvinyl alcohol (PVA, 1 g) (Mw = 89 × 103 g/mol, Sigma Aldrich) was dissolved in DI water (120 ml) that to prepared the host polymer. Then, 3 ml of these host polymer were mixed with a graphene suspension (2 ml) [21] and the resultant mixture was used in chemical spray system. On the other hand, graphite sample prepared by scratch it's surface by a graphite-rich pencil [22]. The coating process was performed using remote-controlled chemical spray system. Graphene and graphite were coated on Al substrate respectively as shown in Fig. 1.

Fig. 2 shows the wind tunnel that was used to investigate the heat transfer performance.



(a) (b) (c)

Fig. 1 Photographs and enlarged images (× 85) for samples: (a) uncoated (b) coated by graphite and (c) coated by graphene.

The experimental set up consists of a 2300 mm long rectangular duct made of thermal insulated polycarbonate glass. Variable speed centrifugal blower is fixed at the inlet of the duct to drive the air through test section. The cross section of the duct is 100 mm × 100 mm. The test section in channel is kept at a distance of 1800 mm (12 times Dh) from the inlet side to ensure fully developed flow in the test section region. Plate heater has been used with the same dimension of the base plate to supply uniform heat flux at the base of micro heat sink. The power supplied to the heater is controlled by programmable DC power supply. A heat sink compound (HC-131) of high thermal conductivity was applied between the heater plate and the base plate of heat sink to reduce the contact resistance to heat flow. Four thermocouples "type k" (FLUKE 87 V, USA) was used to measure the temperature of the micro heat sink base, the outlet temperature of the air stream in the downstream region of the test section, the duct internal surface walls temperature, and the ambient temperature. The average air inlet velocity inside the duct and also the inlet temperature of the air stream has been measured using anemometer (TSI incorporated 9545, USA) located after the flow straightener. In addition, infrared thermometer has been used to measure the average temperature of the heat sink upper surface area. The top wall of the test section in the wind channel has a cut-out region to enable these infrared thermography systems to measure the surface temperature distribution of the heat sink in the test section.

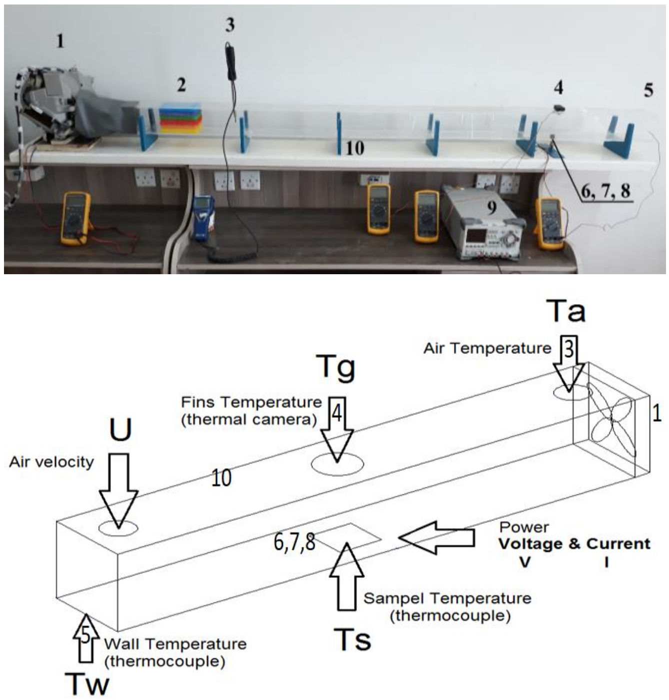


Fig. 2 Photograph view of experimental setup: 1- Centrifugal blower, 2- Flow Straightener, 3- Anemometer and Inlet thermocouple, 4- Thermal camera/Infrared thermometer, 5- Outlet thermocouple, 6- Heater, 7- Plate fin heat sink, 8- Plate fin thermocouple, 9- Programmable DC power supply, and 10- Long rectangular duct.

Figure 3 show the schematic of the heater, heat sink, base plat with heat sink compound.

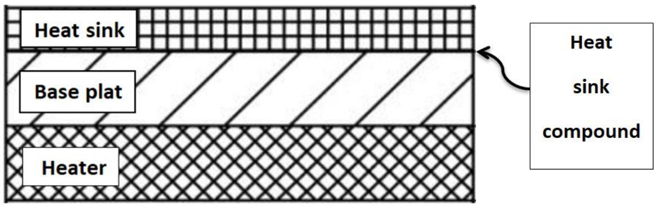


Fig. 3 Schematic diagram for heat sink.

The experimental setup was made to generate fixed amounts of heat fluxes for each sample and to measure both side temperatures. The heat transfer coefficient, thermal resistance, and Nusselt number were calculated for each sample for a range of Reynolds number. The waiting time was about 30 min to achieve the steady state, where the temperature reading variations were within ± 0.1 °C. Table 1 depicts a comparison between graphite and graphene and aluminum in thermal properties.

3. Calculations

The assumptions used in this paper are: the channel walls are thermally insulated, steady state of electric power (current and voltage), incompressible fluid (air), fully developed flow at the test section, the heat flux is constant and uniform and the heat removed from the heat sink is assumed to be transferred by conduction, convection and radiation.

The parameters characterizing the fluid flow of the air and heat transfer inside the wind tunnel with micro-heat sink are defined as following [26]. The main percentage of the power, Q_{power} provided by the heater to the micro heat sink sample is transferred into the air flow by convective heat transfer Q_C and conductive heat transfer Q_k while a minor, but far from negligible, portion of power Q_{power} is transferred to the wind channel walls through radiative heat transfer Q_r.

Table 1 Thermal properties comparison between commonly used materials for heat spreading.

property	**Natural Graphite sheet (eGraf) [23]**	**Theoretical properties of Graphite [7]**	**Graphene Nano plate sheet**	**Aluminum Alloy 1050 [24]**
Density (g/cm^3)	1.1-1.7	2.26	2.2 [9]	2.7
Thermal Conductivity (W/mK) in-plane direction	140-500	398 @ 25 °C	3000-5000 @ room Temp. [9]	229
Thermal Conductivity (W/mK) through thickness direction	3-10	2.2 @ 25 °C	3000-5000 @ room Temp. [9]	229
Specific Heat Capacity	846	690-719 25°C	700 [25]	921

The radiative heat transfer is given by;

$$Q_r = \sigma \,.\, \epsilon \,.\, A \left(T_s^4 - T_w^4\right) \tag{1}$$

Where σ is the Stefan-Boltzmann constant, ϵ is the emissivity of the sample surface, A is the sample surface area, T_s is the sample temperature measured by the thermocouple inserted in the center of the sample, T_w is the temperature of the wind channel wall.

The conductive heat transfer is given by;

$$Q_k = A\, k\, \frac{\left(T_s - T_g\right)}{x} \tag{2}$$

where k, A and x are the sample thermal conductivity, area and thickness. T_g is the temperature of upper surface of heat sink and measured by the infrared thermometer.

The convective heat transfer is given by;

$$Q_c = Q_{power} - Q_r - Q_k \tag{3}$$

$$Q_c = Q_{power} - \sigma \,.\, \epsilon \,.\, A \left(T_s^4 - T_w^4\right) - A\, k\, \frac{\left(T_s - T_g\right)}{x} \tag{4}$$

The power provided by the heater can be calculated as;

$$Q_{power} = V \,.\, I = \frac{V^2}{R} \tag{5}$$

The thermal transmittance T_r is calculated as;

$$T_r = \frac{Q_c}{\left(T_s - T_a\right)} \tag{6}$$

where T_a is the air temperature.

$$T_r = \frac{Q_{power} - \sigma.\, \epsilon.\, A.\left(T_s^4 - T_w^4\right) - A\, k\, \frac{\left(T_s - T_g\right)}{x}}{\left(T_s - T_a\right)} \tag{7}$$

The convective heat transfer can be calculated as;

$$h = \frac{Q_c}{A\left(T_s - T_a\right)} \tag{8}$$

$$h = \frac{Q_{power} - \sigma.\, \epsilon.\, A.\left(T_s^4 - T_w^4\right) - A\, k\, \frac{\left(T_s - T_g\right)}{x}}{A\left(T_s - T_a\right)} \tag{9}$$

The Reynolds number can be calculated as;

$$Re_L = \frac{u \,.\, L}{v} \tag{10}$$

where u is the mean air velocity inside the wind tunnel, L is the characteristic heated edge of the sample, v is the kinematic viscosity of air.

The Nusselt number is given by;

$$Nu = \frac{h \,.\, L}{k} \tag{11}$$

The Prandtl number is given by;

$$Pr = \frac{\nu}{\alpha} \tag{12}$$

where α is the thermal diffusivity of air.

4. Experimental Uncertainties

The method reported by Moffat [27] has been used in this study to calculate the maximum uncertainties of Reynolds and Nusselt numbers. The maximum uncertainties of *Re* and *Nu* are 4.6 % and 7.4 % respectively. Comparing the present experimental results with previously published works showed very good agreement as displayed in Fig. 4. The comparisons were made for uncoated specimen heat sink.

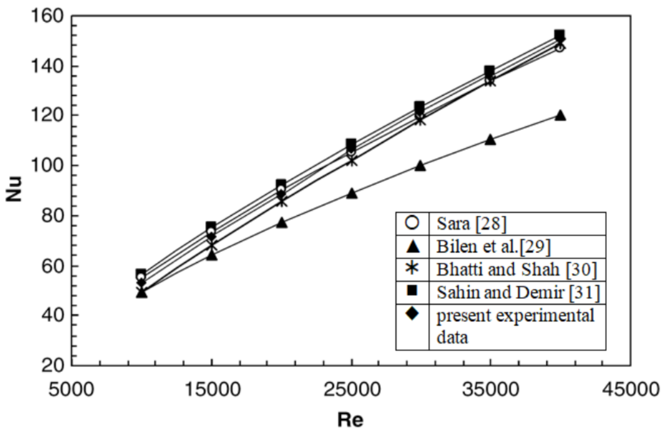


Fig. 4 Comparison of Nusselt numbers for different available experimental results for an uncoated sample.

5. Results and Discussion

The heat transfer characteristics of the coated and uncoated heat sinks was analyzed and presented in detail. The various heat transfer performance parameters were studied experimentally with respect to the two types of coating, graphite and graphene. Raw or uncoated third specimen is included to highlight the role of coating process. Experiments are achieved for various Reynolds numbers.

Figures 5, 6 and 7 show the experimental results of the heat transfer coefficients, Nusselt numbers and the thermal transmittance for tested coated and uncoated heat sink for a Reynolds numbers of 6500, 8500, 11750, and 16500 respectively.

The Nusselt number and the thermal transmittance has been presented for a range of the Reynolds numbers for a turbulent air flow in order to quantitatively represent the performance of the three samples, coated (graphite and graphene) and uncoated of the heat sinks. This figure shows the results of the heat transfer confident, Nusselt number, and the thermal transmittance for each tested heat sink for a range of Reynolds numbers 6500-16500.

Figs. 5, 6 and 7 depict significant roles of both Reynolds number and the type of nanoparticles coating on increasing the heat transfer coefficient h, and hence the Nusselt number Nu. That is the enhancement of both Nu and h with Reynolds number because increasing Reynolds number augments the inertial force which augments in turn the rate of heat exchanging between the forced air and the micro heat sink. The coating process shows an encouraged role of the nanoparticles coating, where both types of nanoparticles highlight an enhancement of Nusselt number and heat transfer coefficient. This is referred to that the graphene layer provides high thermal conductivity layer, and also increase the area of heat exchange by forming roughened island-shaped layer. The enhancements of heat transfer coefficient at *Re* = 12000 are 4% for graphite nanoparticles and 14 % for graphene nanoparticles when compared with uncoated specimen.

Eventually, Fig. 7 shows that the thermal transmittance exhibits similar trends to those of Nusselt number and heat transfer coefficient namely, the increase of transmittance of coated sample, and especially that coated by graphene, with Reynolds number is faster than uncoated one. In other words, the graphene nanoparticles enable the spacemen to devour as possible as the inertial force gained by Reynolds number.

5.1. Surface morphology

Figure 8 (a) and (b) shows the morphology of the surface and Abbott-Firestone curve of UN sample, while Fig. 8 (c) and (d) shows the morphology of the surface and the curve of Abbott-Firestone of sample coated by graphite moreover, Fig.8 (e) and (f) shows the morphology of the surface and the curve of Abbott-Firestone of sample coated by graphene.

ISO 25178 - Primary surface morphology of UN sample showed that the arithmetic mean height (*Sa*) = 12.49 nm, while it is 24.35 nm in graphene sample and for sample which coated by graphite is 11.57 nm. That is referring to increase in the surface roughness by coating a graphene layer.

The increasing in surface roughness can be related to increase of number of grains of graphene layers [32].

At same time, the Abbott-Firestone curve shows that the surface texture has been changed after coating by graphite and graphene layer. Abbott-Firestone curve illustrates that the bearing area emerges in shape referring to the surface structure is comb-shaped structures or abrasive peaks structure, while the graphene coating changed the shape of curve which can contributed to disappearing of abrasive peaks due to coating process, hence the surface texture changed to a kernel structure and that can also explain why the roughness of surface has been increased.

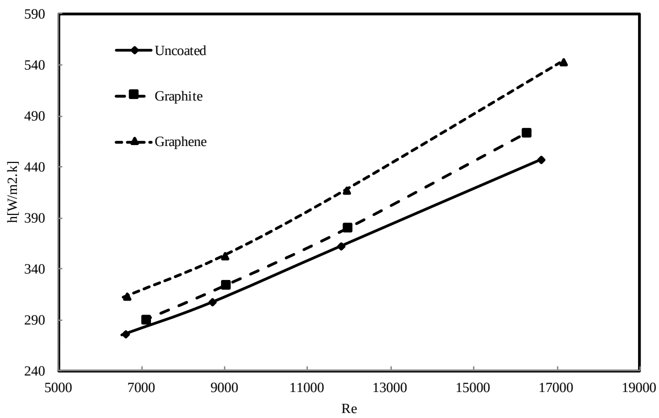


Fig. 5 Heat transfer confident for all studied micro heat sinks samples at different Reynolds number.

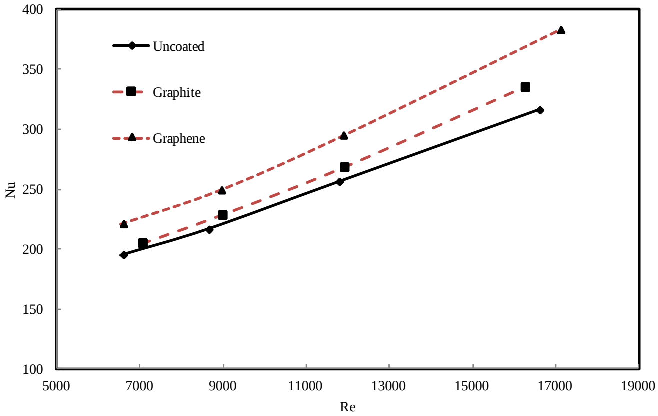


Fig. 6 Nusselt number for all studied micro heat sinks samples at different Reynolds number.

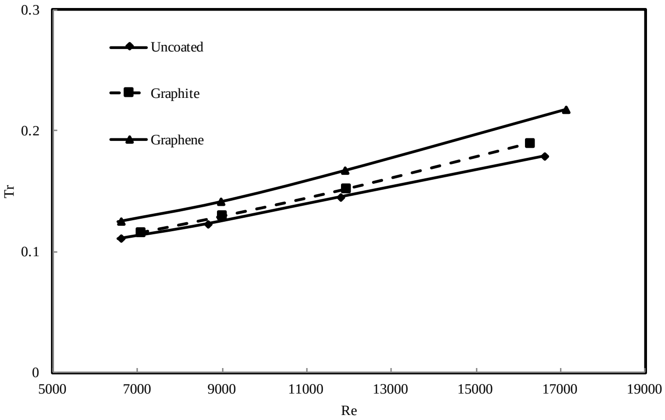


Fig. 7 Thermal transmittance for all studied micro heat sinks samples at different Reynolds number.

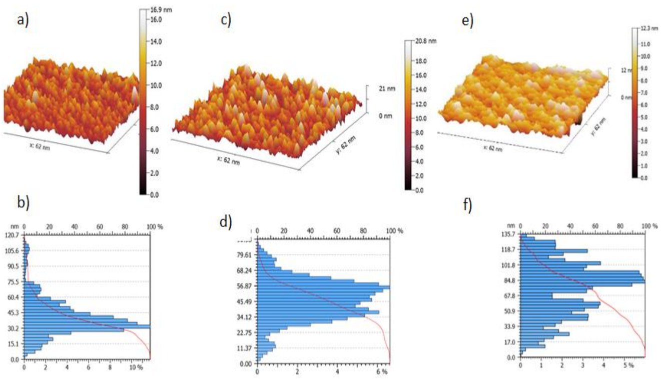


Fig. 8 Surface morphology measured by SPM (a) surface morphology for UN sample (b) Abbott-Firestone curve for UN sample, (c) surface morphology for sample coated by graphite, (d) Abbott-Firestone curve for sample coated by graphite, (c) surface morphology for sample coated by graphene (d) Abbott-Firestone curve for sample coated by graphene.

6. Conclusions

Three samples of aluminum heat sinks are tested in wind tunnel. Two of them have been coated by nanoparticles, graphene and graphite, while the third specimen is pure aluminum for judging task. The experiments were conducted in turbulent Reynolds number. From the calculation of Nusselt number and heat transfer coefficient, it is concluded that:

1. The coating process provides best heat transfer enhancement with graphene nanoparticles results.
2. The enhancements of heat transfer coefficient at *Re* = 12000 are 14 % for graphene nanoparticles and 4 % for graphite nanoparticles when compared with uncoated specimen.

As a continuous investigation, authors of this paper are continuing in testing the role of more coating thicknesses.

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