Drying Graphene Nanofluid on Heated Substrate

P. Chen*, S. Harmand* and M. Bigerelle*

*LAMIH-CNRS Laboratory, University of Valenciennes, Valenciennes, France
pin.chen@etu.univ-valenciennes.fr, souad.harmand@univ-valenciennes.fr,
maxence.bigerelle@univ-valenciennes.fr

ABSTRACT

In this paper, experiments for investigating the evaporation of graphene nanofluid droplets were executed on a heated saphhire substrate whose temperature changed from ambient to 106 ℃. A side view CCD camera was utilized to record the evaporation process for the profile analysis and an infrared camera was used to observe the temperature distribution on the air/liquid interface of the droplets. The results showed that the graphene nanofluid and water had the same behaviour in contact angle and base diameter during evaporation, but the evaporation rate revealed an unexpected result that the water droplet finished faster than graphene nanofluid despite the high thermal conductivity of graphene nanofluid at higher substrate temperature.

Keywords:graphene nanofluid, droplet evaporation, evaporation rate

1 INTRODUCTION

In order to enhance the thermal conductivity of common fluid, the nanoparticles made of metals, oxides, carbides or carbon nanotubes are dispersed in water or ethylene glycol to make nanofluid. Graphene is an important one of them for its extremely high value of thermal conductivity [1,2]. Additionally with the increase of temperature, the enhancement of thermal conductivity of graphene nanofluid augments [3].

Soujit Sen Gupta et al. used the transient hot wire method to measure the thermal conductivity of graphene nanofluids with different concentrations and temperatures and compared the enhancement with other nanofluids [4]. They found that the enhancement of thermal conductivity improves with the increase of concentration and temperature. They supposed that the mechanism of graphene nanofluids' heat conduction is a hybrid model of percolation and Brownian motion.

Madhusree Kole and T. K. Dey investigated the thermal conductivity, viscosity and electrical conductivity of graphene nanofluids compared with base fluid [5]. With 0.395% volume concentration of graphene, the thermal conductivity of nanofluid has a maximal enhancement of 15% at 30 ℃. At the same conditions, the viscosity was enhanced by 100% and the electrical conductivity was enhanced by 87 times that of base fluid.

Kyung Mo Kim and In Cheol Bang used the heat pipes with a screen mesh wick filled of 0.01 and 0.03 vol% graphene oxide/water nanofluids to investigate the thermal performance with nanofluids [6]. By comparing with the water-filled situation, the wall temperature of the GO/water nanofluids-filled heat pipes were found to be lower and the evaporator thermal resistances can be reduced by about 25%.

Although numerous studies have demostrated the high thermal conductivity of graphene nanofluid, the process of droplet evaporation is complex and ambiguous which has attracted the interest of researchers for many years. The full understanding of evaporation process and heat transfer of a sessile droplet is very important to a wide range of industrial applications. In these experiments, the sessile droplets of pure water and 0.25 mg/ml water-based graphene nanofluid are tested at different substrate temperatures and the dynamic evaporations are investigated by a combination of optical and infrared techniques.

2 EXPERIMENTAL SETUP

The sessile droplets of two liquids are formed by the automatic dosing system which can control the volume of droplet as well as dosing speed, and deposited on the sapphire substrates below which there is a black painted heater connected to electrical controller (see Fig. 1). The substrates and heater are placed in a vapor chamber, in which the ambient temperature and the relative humidity can be controlled. A side view CCD camera (Allied Vision Technologies, 780×580 pixels) is used to record the evaporation process of the droplets. A Kruss® Drop Shape Analyzer is used to measure the contact angle, volume, diameter and height of sessile droplets during evaporation by the analysis of droplets profile. The top of the vapor chamber has a sapphire window for the infrared camera and a hole for passing the syringe. The infrared camera (FLIR X6580SC) is installed on top to observe the temperature distribution on the surface of the droplets.

The evaporation of a 1 μl droplet is carried out at an ambient temperature of 20 ℃ and a relative humidity of 30 %. The substrate temperature varies from ambient to 106 ℃ to investigate the influence of substrate temperature on the evaporation process.

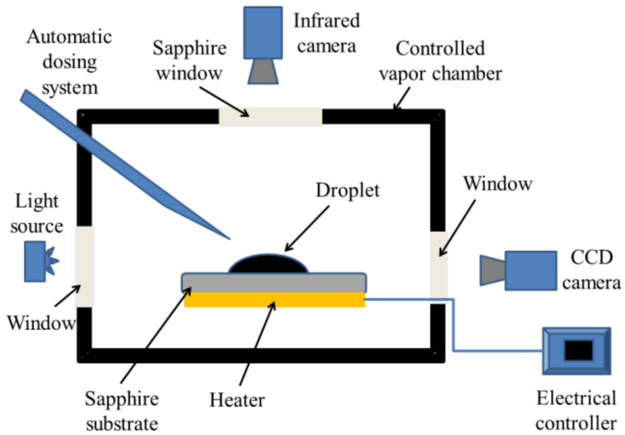

Figure 1: Schema of the experimental setup.

3 EXPERIMENTAL RESULTS

The optical and infrared techniques are applied to investigate the dynamic evaporation of droplets of graphene nanofluid and base fluid. The CCD camera records the evaporation process and then the software Kruss® Drop Shape Analyzer analyzes the profile of droplets and the evolutions of droplets' contact angle, volume and diameter are accessible. On the other hand, the infrared camera records the evporation process at the top view and provides the dynamic temperature distribution on the surface of the droplets.

Based on the measurements of each frame of videos recorded by CCD camera, the evolutions of contact angle, volume and diameter of droplets as a function of time are presented in Fig. 2.

During the evaporation process, the droplet of graphene nanofluid had the similar behaviour as that of base fluid. The contact angle decreased once the droplet was deposited on the substrate while the contact diameter remained constant for most period of evaporation. When coming to the end of evaporation, the contact diameter reduce abruptly. At this moment, the "stick-slip" phenomenon appeared for the case of water. However for graphene nanofluid, the contact angle increased slightly and then decreased to zero. Meanwhile, the sharp shrink of contact diameter slowed down but immediately returned to the previous reduction speed again. These comportments at final stage of evaporation are observed evidently in the videos recorded by CCD camera. When normalizing the value of contact diameter for both liquids (see Fig. 3), we can notice that the droplets of water always began to shrink earlier than that of graphene nanofluid. This can be explained by that the nanoparticles are driven by the outward capilary flow to form agglomerations at the wedge of droplet and maintain the pinning of contact line [7]. The evolutions of volume have the same mode for the droplets of both liquids. The volume decreased almost linearly from the beginning of evaporation until the last stage when the contact diameter began to reduce, the evolution of volume had a gentler slope. This is because the reduction of diameter leads to shorter contact line where the main evaporation of liquid happens.

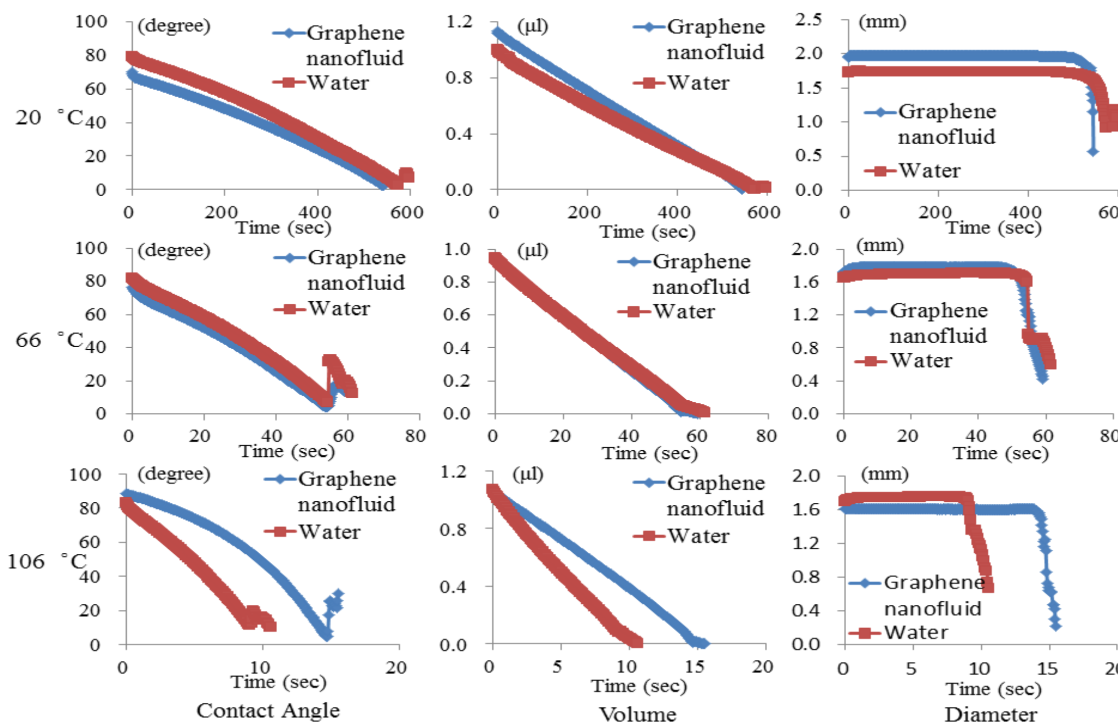

Figure 2: Evolutions of the contact angle, volume and diameter for graphene nanofluid and water under different substrate temperature conditions versus time

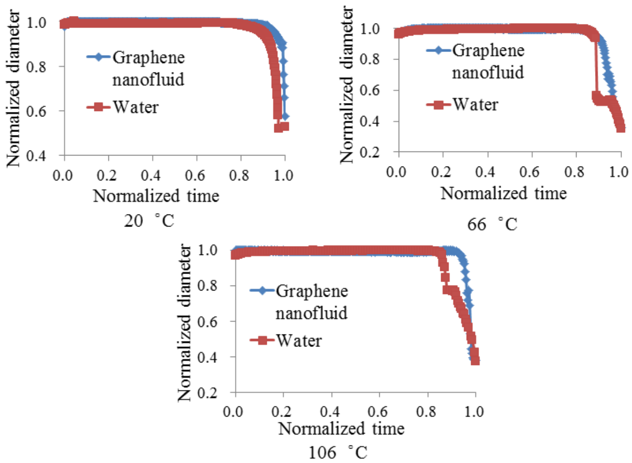

Figure 3: Evolutions of the normalized diameter as a function of normalized time under different substrate temperature conditions.

The tests were executed in different substrate temperatures and the results showed that substrate temperature has no evident influence on the evolution mode of the contact angle, volume and diameter. However, the substrate temperature plays an important role in determining the time when the droplet evaporates thoroughly. At lower substrate temperature, the droplet of graphene nanofluid finished a little earlier than that of water with the same volume. On the contrary, the droplet of graphene nanofluid lasted much longer than that of water at higher substrate temperature. At medium substrate temperature, the droplets of both liquds completed evaporation nearly at the same time. On the basis of the evaporation time and the initial volume of droplet, the total evaporation rate at different substrate temperatures are obtained and showed in Fig. 4. The calculation of total evaporation rate is the average of the results from a series of 6 tests for each substrate temperature condition. With the increase of substrate temperature, the total evaporation rates of droplets of both liquids augment significantly. Moreover, at the highest temperature(106 ℃), water has much higher evaporation rate than graphene nanofluid. The inset is an enlarged view for the situation of lower substrate temperature (20 ℃ and 50 ℃) which indicates that the heat transfer efficiency of graphene nanofluid is better than water at lower substrate temperatures. Table 1 represents the enhancement of evaporation rate of pure water droplets by addition of graphene nanoparticles. The negative values signify the degradation of the evaporation rate. At 20 ℃ substrate temperature, adding graphene nanoparticles can enhance the evaporation rate of water droplet by the maximal value of 25.8% and subsequently the enhancement decreases with the increase of substrate temperature. Furethermore, between 66 ℃ and 84 ℃, there exists a transition stage where the droplets of water and graphene nanofluid have the equivalent evaporation rate.

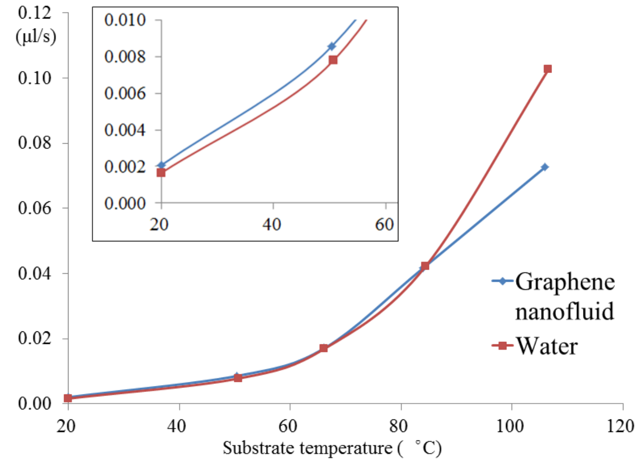

Figure 4: Total evaporation rate for graphene nanofluid and water as a function of substrate temperature.

Substrate temperature	Enhancement of total evaporation rate
20 ℃	25.8%
50 ℃	9.8%
66 ℃	1.2%
84 ℃	-1.1%
106 ℃	-29.2%

Table 1: Enhancement of total evaporation rate with addition of graphene nanoparticle based on that of water.

4 CONCLUSIONS

Deposited on sapphire substrate under different substrate temperature conditions, the droplets of water and graphene nanofluid have demonstrated similar evolutions of the contact angle, volume and diameter. At the last stage of evaporation, while the contact diameter began to shrink, the "stick-slip" phenomenon appeared for the case of water droplet. However the contact angle of graphene nanofluid droplet jumped only once. Substrate temperature is found to be a key influencing factor for the evaporation rate. With high thermal conductivity, the droplet of graphene nanofluid possesses the higher evaporation rate than that of water at ambient temperature. The enhancement of evaporation rate reaches the maximal value at ambient temperature and then decreases with the further increase of substrate temperature. The opposite situation was observed at substrate temperature of 106 ℃, the water droplet evaporated much faster than the graphene nanofluid droplet. The droplet evaporation is a complicated process, more factors, for example dynamic viscosity, Marangoni flow, drop profile, nanoparticle shape, need to be considered in the determination of nanofluid droplet's evaporation rate.

REFERENCES

[1] A. A. Balandin, S. Ghosh, W. Z. Bao, I. Calizo, D. Teweldebrhan, F. Miao and C. N. Lau, Nano Lett., 8, 902, 2008.

[2] S. U. S. Choi, Z. G. Zhang, W. Yu, F. E. Lockwood, and E. A. Grulke, Appl. Phys. Lett., 79, 2252, 2001.

[3] T. T. Baby and S. Ramaprabhu, J. Appl. Phys. 108, 124308, 2010.

[4] S. S. Gupta, V. M. Siva, S. KRISHNAN, T. S. Sreeprasad, P. K. Singh, et al., J. Appl. Phys., 110, 084302, 2011.

[5] M. Kole and T. K. Dey, J. Appl. Phys., 113, 084307, 2013.

[6] K. M. Kim and I. C. Bang, International Journal of Thermal Sciences, 100, 346-356, 2016.

[7] K. Sefiane, J. Skilling, and J. MacGillivray, Advances in colloid and interface science, 138(2), 101-120, 2008.