Evaporation of Gold Nanofluid Sessile Drops on Heated Substrate

I. Zaaroura*, S. Harmand* , J. Carlier** and R. Boukherroub***

*LAMIH Laboratory-UMR-CNRS 8201, Université Polytechnique Hauts-de-France, Valenciennes, France, ibrahim.zaaroura@etu.uphf.fr, souad.harmand@uphf.fr
**IEMN Laboratory-UMR-CNRS 8520, Université Polytechnique Hauts-de-France, Valenciennes, France, julien.carlier@uphf.fr
*** IEMN Laboratory-UMR-CNRS 8520, Université de Lille, Lille, France, rabah.boukherroub@univ.lille.fr

ABSTRACT

In this paper, experiments investigating the evaporation of gold nanofluid droplets to evaluate the effect of the particle size (5 and 10 nm) and concentrations (1 and 4% C_v), were executed on a hydrophobic silicon substrate at different surface temperature (amb, 60 and 80 °C). A drop shape analyzer was utilized to record the evaporation process for the profile used under the same conditions (50% humidity, T_{atm}=25 °C). Also, an infrared camera is used to observe the droplet surface gradient temperature, air/liquid, at the same time. The analysis focus on the influence of size and concentration of nanoparticles on the evaporation rate compared to the base fluid (distiled water). In addition, the effect of gradient surface temperature instabilities due to Marangoni cells on the dynamic deposition of nanoparticles at the surface is examined [1].

Keywords: Gold nanoparticles, Droplet evaporation, Evaporation rate, Marangoni cells

1 INTRODUCTION

In recent years, nanofluids have received a great deal of attention because of their potential use in many applications. Nanofluids represent a new and innovative class of heat transfer fluids that can be used in a variety of fields, including engine cooling, heat exchangers, microelectronics, fuel cells and so on [2,3]. To clarify our research in improving heat transfer using nanofluids and before design any thermal system in which nanofluid is the working fluid, it is necessary to know their thermophysical properties including thermal conductivity [4,5], viscosity [6], density and heat capacity in addition to their stability. In order to enhance the thermal conductivity of common fluids, nanoparticles made of metal, oxides or carbon nanotubes are dispersed in water or other base fluid to make nanofluid. Gold nanoparticles with different sizes, 5 and 10 nm, are used as nanofluid in our experiments to show the size effect of nanoparticles on the efficiency of heat transfer in addition to their concentrations change. Different methods can be used to measure the thermal conductivity of gold nanoparticles, experimentally like transient hot wire method [7] and using some empirical models [8,9]. Thermal conductivity can be affected by different parameters: particle volume fraction, temperature, particle size, pH. Natallia Shalkevich et al. measured the thermal conductivity of different gold nanoparticles at different particle size and volume fraction [7]. Despite the importance of thermal conductivity in heat transfer, it should also take into account some other parameters such as viscosity because of its effect on the evaporation rate [10]. In this experiment, sessile droplets of pure water, (1 and 4% C_v) 5 nm Au-water based nanofluid and (1 and 4% C_v) 10 nm Au-water based nanofluid are tested at different substrate temperatures and the dynamic evaporation are investigated thanks to a combination of optical and infrared techniques.

2 EXPERIMENTAL SETUP

In this work, the studied nanofluid consists of gold (Au) nanoparticles, stabilized suspension in 0.1mM PBS reactant free, solved in distilled water. Thus, two different sizes, 5 and 10 nm, are used to study the effect of nanoparticle size on droplet evaporation. Moreover, the effect of concentration (1 and 4%C_v) on the evaporation process has been done. The Au-water sessile droplets are formed by an automatic dosing system which can control the volume of droplet as well as dosing speed, and deposited on the silicon substrate where a resistance wire is connected to electrical controller (see Fig. 1). The substrate and heater are placed in a vapor chamber, in which the ambient temperature and the relative humidity can be controlled. A side view CDD camera (Allied Vision Technologies, 780x580 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 the 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 the top to observe the temperature distribution on the surface of the droplets.

The evaporation of a 1.5 µl droplet is carried out at an ambient temperature of 20 °C and a relative humidity of 50 %. The substrate temperature varies from ambient to 80 °C to investigate its influence on the evaporation rate.

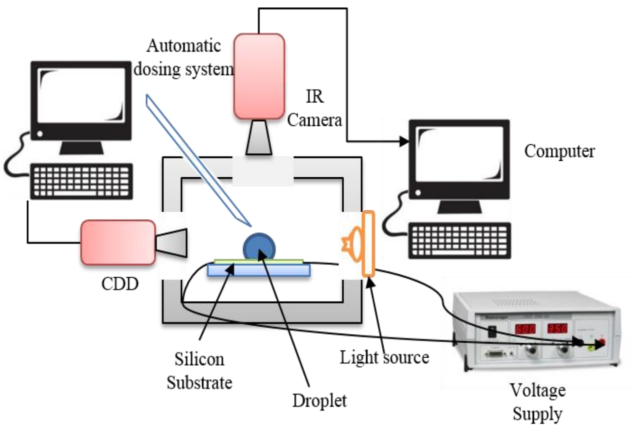


Figure 1: Schema of the experimental setup

3 EXPERIMENTAL RESULTS

The optical and infrared techniques are applied to investigate the dynamic evaporation of droplets of gold (Au) nanofluid. Two different sizes (5 and 10 nm) compared to base fluid (pure water). The CCD records the evaporation process and then the software Kruss Drop Shape Analyzer analyzes the profile of droplets and the evolution of droplets, contact angle, volume and diameter, are accessible. Moreover, the infrared camera records the evaporation process at the top view and provides the gradient temperature distribution on the surface of the droplets.

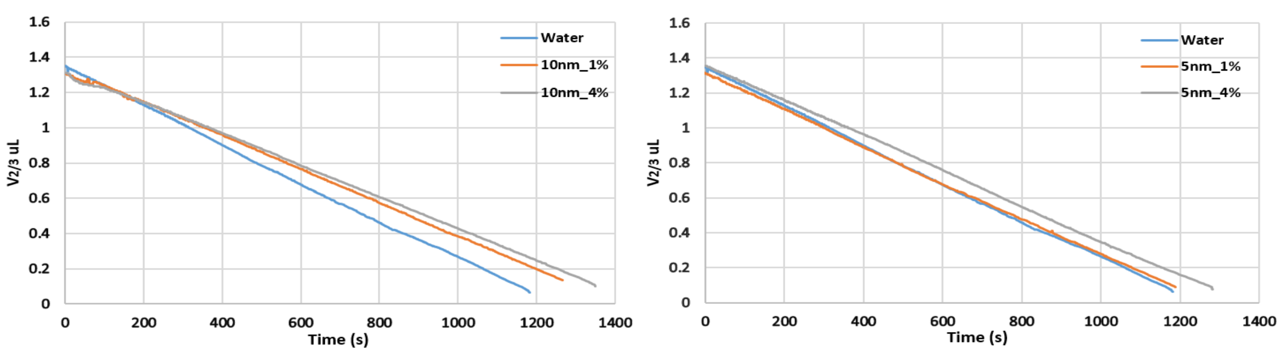
Based on the measurements of each frame of videos recorded by CCD camera, the evolution of volume ($V^{2/3}$) as a function of time is presented in Fig. 2.

Firstly, we observed that the evolution of diameter and contact angle are the same for all droplets (gold and pure water droplets at different surfaces temperature). The evolution of volume have the same trend for the droplets of both liquids. The test were executed on different substrates temperature with no change or influence on the evolution mode of the contact angle, volume and diameter. So, substrate temperature plays an important role in determining the time when the droplet evaporates totally. At ambient temperature, the droplet lifetime of pure water was a little lower than that of Au-water nanofluids for both diameter (5 and 10 nm). At 60 °C surface temperature, the evaporation of 5nm Au-water nanofluid droplet with 1 and 4% C_v was faster than that of water droplet with the same volume and conditions. As the surface temperature increased to 80 °C, the evaporation rate of the 5 nm Au-water nanofluid (1 and 4% C_v) was higher than the water evaporation (Table 1). For all surface temperature, the increase in the concentration led to decrease in the evaporation rate of the droplet was still higher than pure water evaporation rate.

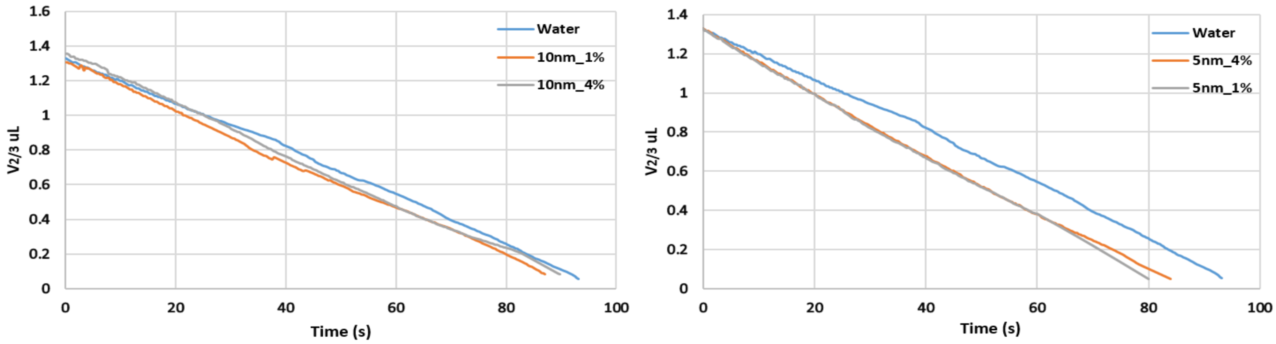
Same measurements were done with the 10 nm gold nanoparticle at same surface temperatures. The evaporation of 10 nm Au-water nanofluid droplets was higher than pure water with very small percentage (3~4 %) with the two concentrations and at two surface temperatures (Table. 1).

Substrate temperature °C	**Enhanement of total evaporation rate, %**			
	5 nm		**10nm**	
	1%	**4%**	**1%**	**4%**
20	-9%	-10%	-18%	-20%
60	+17%	+13%	+3%	+7%
80	+40%	+16%	-8%	+4%

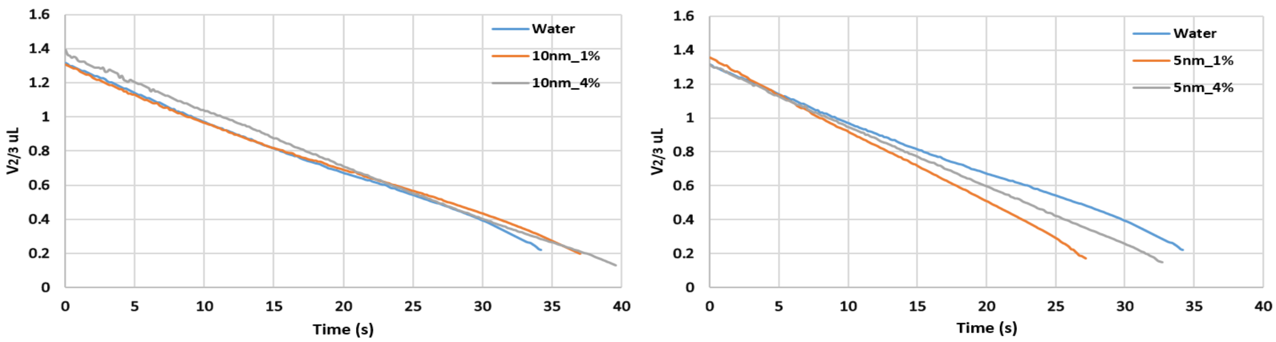
Table 1: Total evaporation rate with addition of gold nanoparticles having different diameters, 5 and 10 nm, at different volume fractions, relative error ≈±4%.



(a)



(b)



(c)

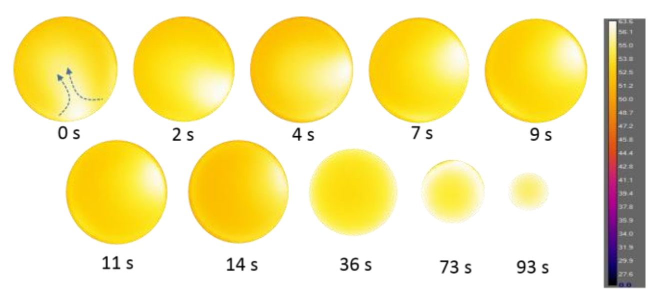
Figure 2: Evolutions of the volume for water and gold nanofluid (different concentrations)under different substrate temperature conditions (a) at ambient, (b) 60 °C and (c) 80 °C versus time.

The faster evaporation process with the smaller size in nanoparticle (5 nm) can be linked to different reasons. The effective surface area of 5 nm Au-water is greater than the 10 nm Au-water droplet by a factor 2, which means increase in reactivity. Nevertheless, the decrease in the evaporation rate after the increasing in the concentration is due to the viscosity effect specially at the end of the evaporation process. Table. 3 shows the increase in viscosity as an increase in the volume fraction. Thus, the viscosity of 10 nm gold nanoparticles was less than that of 5 nm in size and both values are not higher than water viscosity. These values were calculated by applying the model of Corcione [11]. Furthermore, infrared camera images made it possible to detect the convection cells (see Fig. 2), due to the Marangoni effect, that appeared at the droplet surface.

These convection cells increase the vapor mass transfer at the liquid-air interfaces and induce faster evaporation rate. So, the convection cells lifetime, (Table 2), for the 5 nm Au-water has a longer period compared to the 10 nm and pure water. This means that convection flows (Marangoni cells) increases the evaporation [12].

Latent heat here also add another reason explaining the higer evaporation with smaller size gold nanoparticles. The higher evaporation rate (*K*) of (5 nm) Au-water droplet means less latent heat compared to the pure and 10 nm sessile droplet [13].

This relation was proved by D^2-law [14], Eq. 1. Moreover, latent heat will affect the strength of bond between gold nanoparticles and water molecules. As a results, less latent heat (in 5 nm Au-water) makes the strenght of these bonds very weak and break easily (evaporate rapidly) compared to the case with 10 nm Au-water nanofluid.



(a)

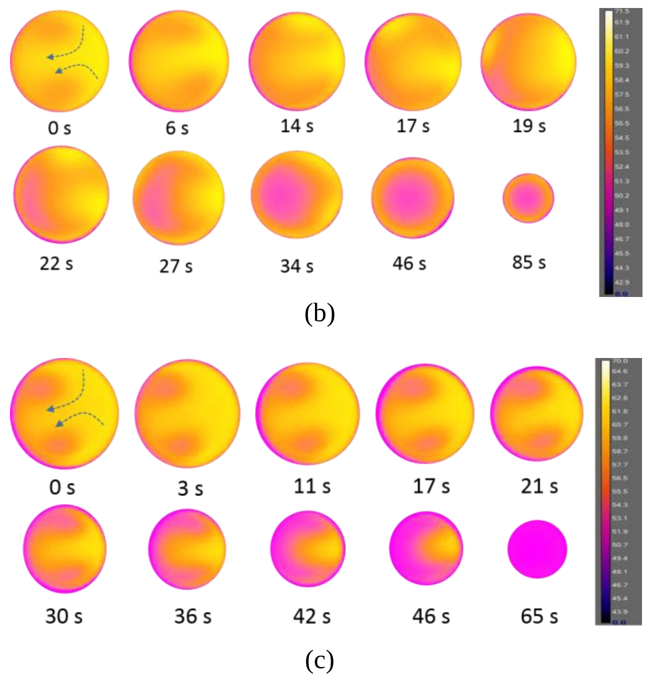


Figure 3: Snapshots from an infrared video of the evaporation process of (a) pure water (b) 10 nm Au-water and (c) 5 nm Au-water nanofluids at 50 % relative humidity and 60 °C surface temperature, 1%C_v.

Fluids/medium	**Convection cells lifetime (sec)**
Water	9
10 nm Au-water,1% C_v	30
5 nm Au-water, 1% C_v	46

Table 2: Lifetime of the convection cells at 60 °C substrate temperature of pure water, 5 nm Au-water and 10 nm Au-water nanofluids.

$$K \propto 1/h_{fg} \qquad h_{fg} = Q_{in}/m_{vapor} \qquad (1)$$

Therefore, the smaller size of gold nanoparticles gave us a very good results related to the heat transfer due to the increase in the thermal conductivity (see Table 4), were calculated by applying the model of Leong at al. [8] Eq. 2 and the creation of Marangoni cells. Moreover, as the size of nanoparticles with diameter less than 10 nm led to increase of the of effective atoms number at the surface of

$$k_{eff} = \Big((k_p - k_{lr})\emptyset_p k_{lr}\big[2\beta_l^3 - \beta^3 + 1\big] + (k_p - 2k_{lr}) \times \beta_l^3\big[\emptyset_p \beta^3 (k_{lr} - k_f) + k_f\big] \Big(\beta_l^3 (k_p + 2k_{lr}) - (k_p - k_{lr})\emptyset_p\big[\beta_l^3 + \beta^3 - 1\big]^{-1} \qquad (2)$$

gold nanoparticles whereas, for larger size of nanoparticles (from 10 nm and more) the percentage of atom on the surface is very small because most of the atoms inside the particles [12].

Substrate temperature ° C	**Viscosity, *μ* (*mPa.s*)**				
	Water	**10 nm**		**5 nm**	
		1%	**4%**	**1%**	**4%**
20	1.001	1.06	1.31	1.07	1.42
60	0.466	0.494	0.612	0.501	0.660
80	0.354	0.375	0.465	0.380	0.502

Table 3: Dynamic viscosity of water and gold nanofluids as a function of volume concentrations and at different substrate temperatures.

Substrate temperature ° C	**Thermal conductivity, *k* (*W.m^{-1}.K^{-1}*)**				
	Water	**10 nm**		**5 nm**	
		1%	**4%**	**1%**	**4%**
20	0.598	0.644	0.789	0.662	0.864
60	0.651	0.701	0.859	0.721	0.941
80	0.677	0.718	0.880	0.738	0.964

Table 4: Thermal conductivity of water and gold nanofluids as a function of volume concentrations and at different substrate temperatures.

4 CONCLUSION

In this paper, a series of experiments were carried out to evaluate the effect of the nanoparticles size and concentration on the evaporation rate and thermal conductivity of gold nanofuids. We synthesized spherical gold nanoparticles of different size (5 and 10 nm) stabilized suspension in 0.1M PBS, reactant free, at two different volume fractions (1% , 4%). The results showed that the decrease of the particles size led to enhance in thermal conductivity (model). At the same time, the evaporation rate of nanofluid with 5 nm gold nanoparticles had the highest enchancment as the surface temperature increased while a decrease in the rate was observed after increasing the volume fraction (4% C_v) and this decrease can be related to the viscosity effect. Also, the viscosity of both 5 and 10 nm gold nanoparticles are not much high than pure water. The opposite situation was observed when we used 10 nm gold nanoparticles. The heat transfer enhancement was very low (4~5 % evaporation rate) even at higher surface temperature. The variations between these two different sizes were due to different reasons. The total effective surface area in 5 nm Au-water nanofluid was higher than that of 10 nm Au-water nanofluid by factor 2. Furthermore, convection cells due to Marangoni effect have been detected by an infrared camera focused at droplet surface. The results showed that the lifetime of these convection cells at 5 nm Au-water droplets was longer than that of 10 nm Au-water drops and pure water too. Finally, droplet evaporation is a complicated process, more factors, for example of dynamic viscosity, Marangoni flow, drop profile, nanoparticle shape, need to be considered in the determination of nanofluid droplet's evaporation rate.

REFERENCES

[1] I. Zaaroura, M. Toubal, H. Reda, J. Carlier, S. Harmand, R. Boukherroub, A. Fasquelle, B. Nongaillard, Evaporation of nanofluid sessile drops: Infrared and acoustic methods to track the dynamic deposition of copper oxide nanoparticles, Int. J. Heat Mass Transfer 127, Part B (2018) 1168-1177.

[2] W.C. Wei, S.H. Tsai, S.Y. Yang, Kang, S.W. Kang, Effect of Nanofluid on Heat Pipe Thermal Performance, 3rd IASME/WSEAS Int Conf on Heat Transfer, Thermal Eng. Environ. (2005) 115-117.

[3] O. Mahian, A. Kianifar, S.Z. Heris, D. Wen, A.Z. Sahin, S. Wongwises, Nanofluids effects on the evaporation rate in a solar still equipped with a heat exchanger, Nano energy 36 (2017) 134-155.

[4] L. Dongliang, P. Hao, L. Deqing, Thermal Conductivity Enhancement of Clathrate Hydrate with Nanoparticles, Int. J. Heat Mass Transfer 104 (2017) 566-573.

[5] U. Choi, Enhancing thermal conductivity of fluids with nanoparticles, ASME Fluid Eng. Div. 231 (1995) 99-105.

[6] R. Prashera, D. Song, J. Wang, Measurements of nanofluid viscosity and its implications for thermal applications, Appl. Phys. Lett. 89 (2006) 133108.

[7] N. Shalkevich, W. Escher, T. Burgi, B. Michel, L. Si-Ahmed, D. Poulikakos, On the Thermal Conductivity of Gold nanoparticle Colloids, Langmuir 26 (2) (2010) 663-670.

[8] K.C. Leong, C. Yang, S.M.S. Murshed, A model for the thermal conductivity of nanofluids-the effect of interfacial layer, J. Nanoparticle Res., 8 (2) (2006), pp. 245-254.

[9] R. Prasher, Thermal Conductivity of nanoscale Colloidal Solutions (Nanofluids), Phys. Rev. Lett, 94 (2005) 025901.

[10] P. Chen, S, Harmand, M. Bigerelle, Drying Graphene Nanofluid on Heated Substrate, Conference Paper May (2016) TechConnect World Innovation, National Innovation Summit and National SBIR/STTR Conference, At Washington, DC.

[11] Corcione M, Empirical correlating equations for predicting the effective thermal conductivity and dynamic viscosity of nanofluids. Energy Convers Manage 52 (2011) 789–793

[12] P. Chen, S. Harmand, S. Ouenzerfi, J. Schiffler, Marangoni Flow Induced Evaporation Enhancement on Binary Sessile Drops, J. Phys. Chem, B, 121(23) (2017) 5824-5834.

[13] S. Tanvir, S. Jain, L. Qiao, Latent heat of vaporization of nanofluids : Measurements and molecular dynamics simulations, J. Appl. Phys. 118 (2015) 014902.

[14] R. Hung.Chen, T. X.Phuoc, D. Martello, Effects of nanoparticles on nanofluid droplet evaporation, Int. J. Heat Mass Transfer 53 (2010) 3677-3682.