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Influence of surface curvature on sessile droplet contact angle of nanofuids

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Abstract

This paper deals with the change in contact angle of droplets for three nanofluids, i.e., water-Al_2O_3, water-TiO_2 and water-Cu. Nanoparticles were tested at the concentration of 0.01, 0.1, and 1% by weight. Although dispersants were not used to stabilize the suspension, the solutions tested exhibited satisfactory stability. Ultrasonic vibration was used in order to stabilise the dispersion of the nanoparticles. Experimental measurements were performed for horizontal stainless steel (316) tube of three diameters, i.e., 1.6, 3 and 5 mm, and flat stainless steel plates. The results obtained show that the contact angle of tested nanofluids depends strongly on nanoparticle concentration as well as the curvature of the substrate.

Keywords: Contact angle; Nanofluids; Substrate curvature

1 Introduction

Wetting behaviour is of key importance in single phase as well as in two-phase heat transfer processes. For instance, Wu and Cheng [1] established that the laminar Nusselt number and apparent friction constant increase with the increase of the surface hydrophilic property. Hsieh and Lin [2], in turn, indicated that the hydrophilic microchannel has higher local heat transfer coefficient than the hydrophobic microchannel. Wettability affects condensation process, too. Exemplarily, Pulipaka [3] observed that the initial growth rate for the hydrophilic surface is higher than that for the hydrophobic surface. However, it seems, that the most intensively focused topic in the wettability effects in heat transfer is the

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pool boiling [4]. Contact angle affects nucleation ability of the nucleation site [5], bubble departure diameter [6,7], density of active nucleation sites [8], and finally critical heat flux [9]. Therefore, it is of great importance to precisely establish such parameter as contact angle that is the measure of the degree of wetting and represents the angle at which the liquid-vapor interface meets a solid surface.

Several methods of contact angle measurement have been developed [10,11]. Usually a liquid that is placed on a flat solid surface will form a definite angle of contact between the liquid and the solid [12–14]. However, the contact angle was measured while the droplet was placed not only on a flat surface but on the wire [15,16] or tube [17], too. Therefore, the question about the influence of substrate curvature on contact angle is justified.

Recent advances in nanotechnology have allowed development of a new category of liquids termed nanofluids, which was first used by the research group in Argonne National Laboratory, USA [18] to describe liquid suspensions containing nanoparticles with sizes significantly smaller than 100 nm. Scarce literature data show that addition of even small amount of nanoparticles dramatically changes the wetting characteristics [19–21]. Furthermore, it has been postulated that the major reason for critical heat flux improvement in nanofluids is the decrease of static contact angle due to nanocoating formation on the heating surface. The nanocoating – formed on the surface during boiling process of nanofluid, could significantly enhance the surface wettability [22].

The goal of the present work was the experimental determination of the contact angle of three nanofluids, i.e., water-Al_2O_3, water-Cu and water-TiO_2 on horizontal stainless steel tubes of three diameters of 1.6, 3 and 5 mm and flat horizontal plate. Of particular interest was the effect of nanoparticle concentration (0.01, 0.1, and 1% by weight) on droplet contact angle.

2 Experimental

Scheme of the experimental stand used to measure droplet contact angle on horizontal tubes is shown in Fig. 1. Droplets of known volume of 2 μL were injected slowly onto the tube by a syringe. The shape of a droplet on the tube was captured using the digital camera Casio EX-FH25. Tests with sessile droplets on flat horizontal plate were conducted by use of KRÜSS DSA10 goniometer [23] – (Fig. 2).

2.1 Contact angle measurement

Building on digital images of droplets deposited on the tubes two methods of contact angle (α) measurement were applied. First, geometrical approach based

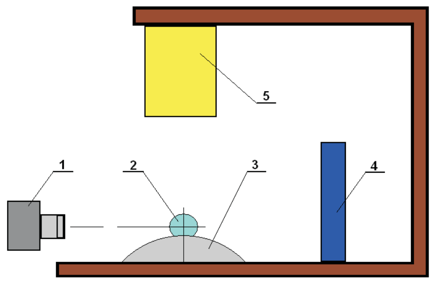


Figure 1. Scheme of the test rig: 1 – digital camera, 2 – droplet, 3 – substrate, 4 – screen, 5 – light source.

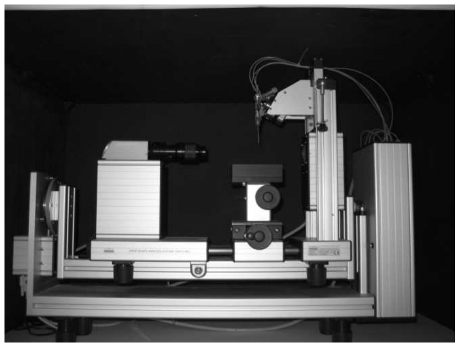


Figure 2. Krüss DSA10 goniometer.

on the relationship (Fig. 3) [24]:

$$\cos \alpha = \frac{r^2 - h^2}{r^2 + h^2}$$

was applied, where r and h are radius and height of the droplet, respectively. Second, a tangent method was developed based on the following algorithm:

1. Choose points along the droplet/air interface and one on the heater surface – Fig. 4,
2. Fit an ellipse through the points on the droplet/air interface.
3. Calculate the tangent at the intersection between this ellipse and the horizontal.
4. Determine the contact angle from the inverse tangent.

For both approaches the average contact angle was calculated as an arithmetic mean of contact angle measurement for 10 droplets.

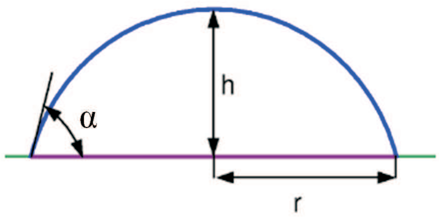


Figure 3. Droplet profile.

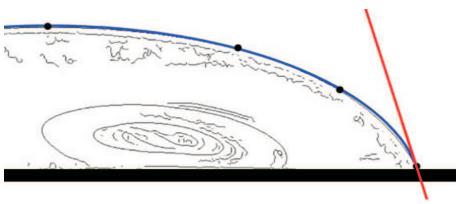


Figure 4. Curve fit and tangent determination.

The uncertainties of the calculated contact angle values based on digital images were estimated using the mean-square method and were equal to $\pm 1°$ for the geometrical approach and $\pm 2°$ for the tangent method [25]. According to the producer of the KRÜSS DSA10 goniometer resolution of contact angle measurement is $0.1°$

2.2 Preparation and characterization of nanofluids

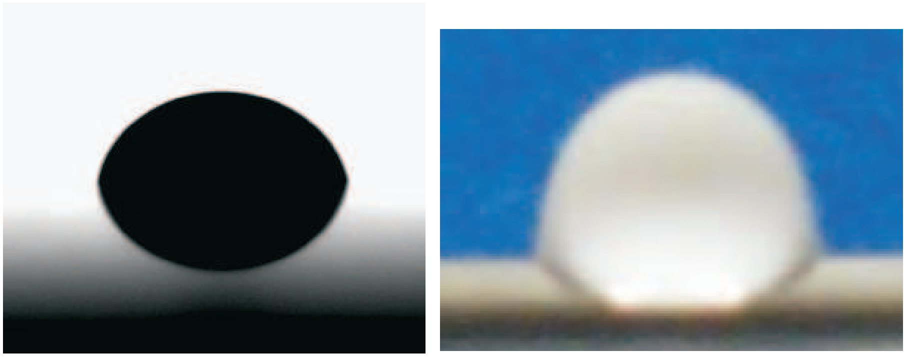
In the present study Al_2O_3, TiO_2 and Cu were used as nanoparticles while distilled, deionized water was applied as a base fluid. Alumina (Al_2O_3) nanoparticles, of spherical form have a diameter ranging from 5 to 250 nm; their mean diameter was estimated to be 47 nm according to the manufacturer (Sigma-Aldrich Co.). Titania (TiO_2) nanoparticles, of spherical form have diameter from 5 to 250 nm; their mean diameter was estimated to be 47 nm according to the manufacturer. Copper nanoparticles of spherical form have diameter from 7 to 257 nm; their mean diameter was estimated to be 48 nm according to the manufacturer. Dispersants were not used to stabilise the suspension. Ultrasonic vibration was used for 30–60 min. in order to stabilise the dispersion of the nanoparticles. Nanoparticles were tested at the concentration of 0.01, 0.1, and 1% by weight. The pH of nanofluids was approx. 7.

2.3 Characteristics of substrate

Contact angles of tested nanofluids were measured on stainless steel (316L) commercially available tubes of three diameters of 1.6, 3 and 5 mm with the average roughness of 0.2, 0.08, and 0.2 μm, respectively. Stainless steel plate was roughed with emery paper 2000 and corresponding average roughness was 0.03 μm.

3 Results

As an example Fig. 5 shows photographs of the sessile droplets of nanofluid water-TiO_2 and nanoparticle concentration of 1% on stainless steel flat plate – photograph taken by goniometer (Fig. 5a) and horizontal tube of 3 mm OD – photograph taken by the digital camera Casio EX-FH25 (Fig. 5b). As an example, Fig. 6 shows the influence of nanoparticle concentration on sessile droplet contact angle of water-Cu nanofluid on stainless steel flat plate and stainless steel tube of 3 mm OD. It is seen in Fig. 6 that the sessile contact angle increases with nanoparticle concentration for flat plate as well as horizontal tube. Furthermore, independent of nanoparticle concentration contact angle for water-Cu nanofluid on flat plate was distinctly higher than that on horizontal tube of 3 mm OD. Interesting is that the contact angle for distilled water on a flat surface was only



a) b)

Figure 5. Images of sessile droplets of water-TiO_2 (1%) nanofluid on a) flat horizontal plate, and b) tube of 3 mm OD.

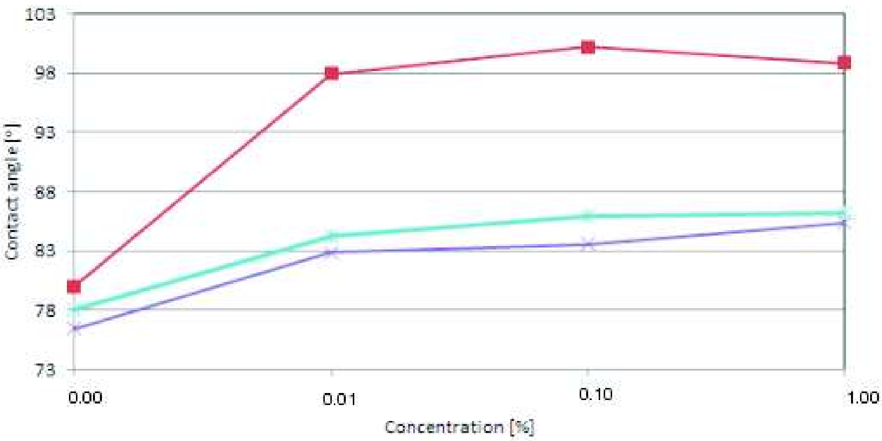


Figure 6. Droplet contact angle of water-Cu nanofluid on stainless steel: **x** – sessile droplet on a tube (geometrical approach), ⋇ – sessile droplet on a tube (tangent method), ■ – sessile droplet on a flat plate (Krüss goniometer.)

slightly higher than on a tube, independent of method of contact angle measurement, i.e., geometrical approach and tangent method. The discrepancy between sessile contact angle estimated by use of geometrical approach and developed tangent method was within $\pm 3^{o}$.

Independent of tube diameter increase in nanoparticle concentration results in decrease of wetting ability for all three tested nanofluids. In Fig. 7 results for the tube of 1.6 mm OD are shown. Figure 7 also shows the uncertainty bars in the contact angle measurement using the tangent method. Noticeable in this plot is that the sessile contact angle for given nanoparticle concentration almost does

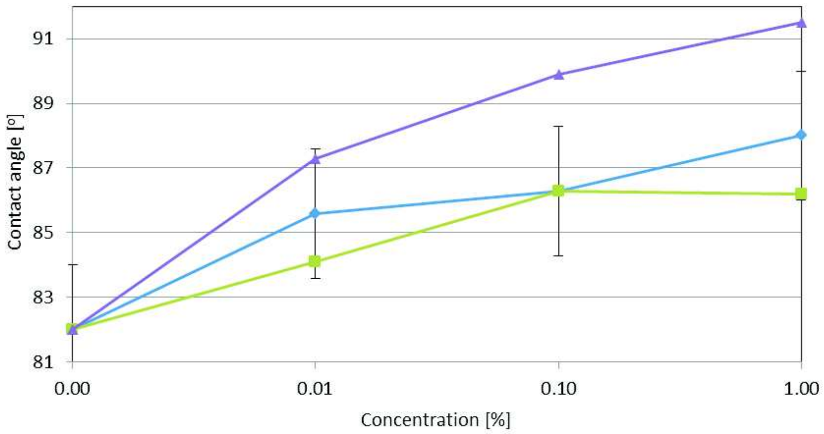


Figure 7. Sessile droplet contact angle of nanofluids on tube of 1.6 mm OD: ♦ – water-Al_2O_3, ■ – water-TiO_2, ▲ – water-Cu.

not depend on the type of nanofluid tested – the results are within the error band of tangent method, i.e., $\pm 2^o$.

Figure 8 to Fig. 10 illustrate influence of tested tube diameters on sessile droplet contact angle of water-Al_2O_3, water-Cu and water-TiO_2 nanofluids, respectively. Geometrical approach was used in order to estimate the sessile droplet contact angle on horizontal tubes, while the sessile droplet contact angle for horizontal flat plate was determined by use of KRÜSS DSA10 goniometer. Characteristic is that the contact angle for distilled water was almost the same for flat surface and all tube diameters. The divergence may result from surface state finish and of course measurement error. For the lowest nanoparticle concentration tested (0.01%) for all three tested nanofluids the lowest contact angle was obtained for the tube with the biggest diameter, i.e., 5 mm. For higher nanoparticle concentration examined (0.1%), except the data for water-Cu nanofluid where contact angle for tube of 5 mm OD was higher than for 3 mm OD tube, the trend was the same as for 0.01% nanoparticle concentration. For the highest nanoparticle concentration tested (1%) the discrepancy between contact angles for all three tube tested diminishes. For all three tested nanofluids the maximal contact angle was obtained for flat surface and nanoparticle mass concentration of 0.1%. For two nanofluids, i.e., water-TiO_2 and water-Al_2O_3 distinct drop of contact angle on flat surface for nanoparticle concentration of 1%, even below the value for distilled water, was observed – Figs. 6 and 8.

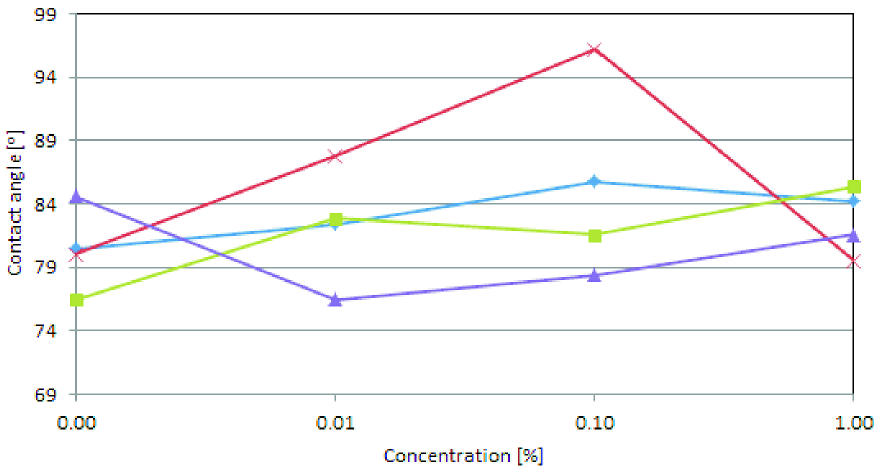


Figure 8. Sessile droplet contact angle of water-Al_2O_3 nanofluid on substrates of various curvature against nanoparticle concentration: ⧫ – tube of 1.6 mm OD, ■ – tube of 3 mm OD, ▲ – tube of 5 mm OD, **x** – flat plate.

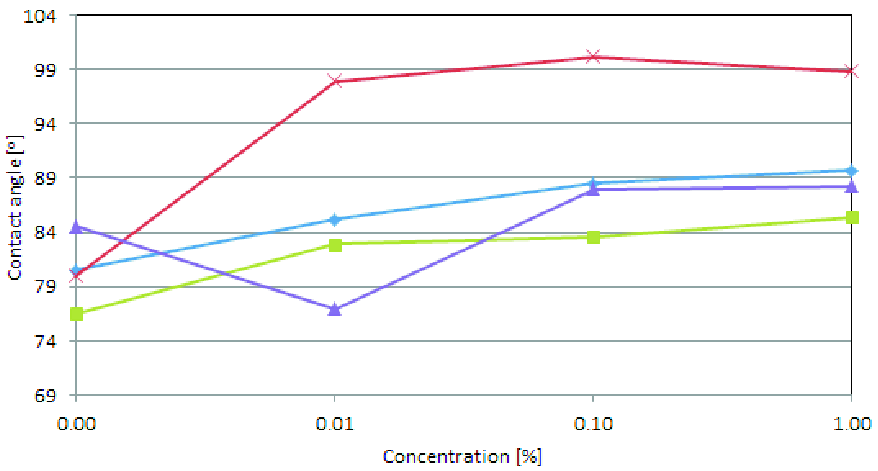


Figure 9. Sessile droplet contact angle of water-Cu nanofluid on substrates of various curvature against nanoparticle concentration: ⧫ – tube of 1.6 mm OD, ■ – tube of 3 mm OD, ▲ – tube of 5 mm OD, **x** – flat plate.

4 Conclusions

The results obtained show that addition of nanoparticles greatly influences the sessile contact angle on stainless steel substrate. The following conclusions were

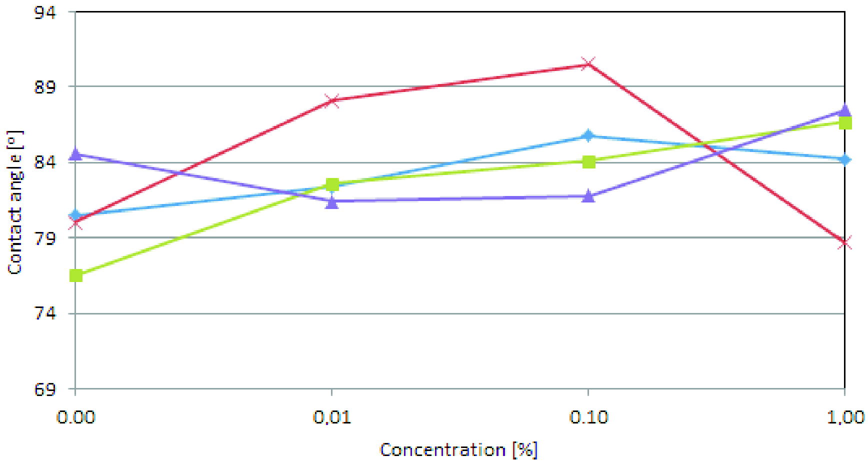


Figure 10. Sessile droplet contact angle of water-TiO_2 nanofluid on substrates of various curvature against nanoparticle concentration: ♦ – tube of 1.6 mm OD, ■ – tube of 3 mm OD, ▲ – tube of 5 mm OD, **x** – flat plate.

drawn after analyzing the experimental results.

- The sessile contact angle increases with nanoparticle concentration for flat plate as well as horizontal tube, although for maximal concetration of the tested nanoparticle (1%) a dramatic drop in contact angle value was noticed for water-TiO_2 and water-Al_2O_3 on flat surface.
- The contact angle for distilled water was almost the same for flat surface and all tube diameters tested (1.6, 3, and 5 mm).
- The sessile contact angle for given nanoparticle concentration almost does not depend on the type of nanofluid tested and tube diameter.
- Generally, an increase in tube diameter results in the decrease of sessile contact angle independent of nanoparticle concentration tested. However, contact angles for flat surface and nanoparticle concentrations of 0.01 and 0.1% are distinctly higher than for all tube diameter tested. This discrepancy may be explained by different surface roughness of flat substrate and tubes.
- It was proved that the developed tangent method gives convergent results as in the case of geometrical approach presented in the literature – restricted to contact angles higher than 30°. Therefore for hydrophilic surfaces the proposed in the paper tangent method is recommended as more general.

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