International Communications in Heat and Mass Transfer 62 (2015) 1–12

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Measurements of the contact angle of nanofluids and development of a new correlation☆

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ARTICLE INFO

Available online 16 January 2015

Keywords:
Concentration
Contact angle
Nanofluids
Particle size
Propylene glycol
Temperature dependence

ABSTRACT

Contact angle measurements were performed on deionized water, propylene glycol and mixture of 60% propylene glycol and 40% water by mass (60:40 PG/W), over a temperature range of 25 °C to 40 °C. All measurements were performed on the surface of a glass slide at the solid–fluid–air-interface. After confirming the contact angle value of water with the data of other researchers, the same procedure was applied to four nanofluids (nanoscale particles dispersed in a base fluid) containing aluminum oxide (Al_2O_3), zinc oxide (ZnO), titanium dioxide (TiO_2) and silicon dioxide (SiO_2) nanoparticles dispersed in 60:40 PG/W. For the nanofluids, the particle volumetric concentrations were varied from 0 to 6% and the average particle sizes ranged from 15 to 50 nm. From the experimental data, it was observed that the contact angles of three single phase liquids and four nanofluids were less than 90°, indicating that all these fluids were wetting to the glass surface. The contact angles of all tested fluids exhibited a continuous decrement with an increase in temperature, and a linear equation for contact angle with temperature matched the data well. For the nanofluids, an increase in the particle volumetric concentration caused a decrease in the contact angle at a constant temperature. The variation of the contact angle followed a second order polynomial relation with the volumetric concentration. For nanofluids at the same volumetric concentration and the same temperature, the contact angles were observed to be lower for larger particle sizes, except for the ZnO nanofluid. A statistical analysis performed on the experimental data yielded a correlation suitable to represent all the nanofluids tested. This contact angle correlation is a function of temperature, volumetric concentration and the size of the nanoparticles, which predicts results successfully with an average deviation of 6.3% from the measured values.

1. Introduction

Contact angles of single phase liquids and their dependence are well-studied subjects, discussed in many books, such as those by Adamson [1] and White [2], just to name a few. Following up from their explanation, when a gas and liquid, separated by their common interface, come in contact with a solid surface, the contact line between the three phases is called the common line. The contact angle θ is the angle between the liquid–solid and liquid–gas interfaces, measured within the liquid. As a rule of thumb, if the contact angel is less than 90°, the liquid is said to wet the solid; if θ is greater than 90°, the liquid is non-wetting. A liquid droplet placed on a smooth horizontal solid surface will attain equilibrium, with a definite angle of contact between the liquid and solid phases, as illustrated in Fig. 1.

As discussed by Adamson the interfacial tensions must be in equilibrium, giving rise to Eq. (1), which is called Young's equation.

$$\gamma_{SL} + \gamma_{SG} + \gamma_{LG} \cos\theta = 0 \quad (1)$$

The contact angle can then be calculated by rearranging Eq. (1)

$$\cos\theta = \frac{\gamma_{SG} - \gamma_{SL}}{\gamma_{LG}}. \quad (2)$$

From fundamental view point, the contact angle is dependent on surface energy and it characterizes the surface wettability. The term wettability describes the contact between a liquid and a solid surface and is a result of intermolecular interactions when the two are brought together. The amount of wetting depends on the energies of the interfaces involved. It is the contact angle that characterizes the degree of wetting. A contact angle of $\theta = 0°$ represents a perfectly wetting condition and $\theta = 180°$ represents a perfectly non-wetting condition.

The effect of droplet size, non-homogeneity and roughness of the solid surface, contamination of the surface, gas/liquid/solid interaction at the contact line, physical properties, and formulation of the interfacial force balance at the contact line are many important factors that affect the contact angle of a fluid [1]. The contact angle is sensitive to the actual physico-chemical conditions of the solid–liquid interface [2]. So, these factors should be kept in mind during experiments.

Glass and metal surfaces possess higher surface energy, compared to plastic, Teflon and wax. As a result, water is extremely wetting to a clean

☆ Communicated by W.J. Minkowycz.

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2014.12.009
0735-1933/

Nomenclature

d_{bf}	base fluid molecule size, nm
d_p	average particle size, nm
g	acceleration due to gravity, 9.81 m/s^2
h_{fg}	latent heat of vaporization, J/kg
T	absolute temperature, K
T_o	reference temperature = room temperature, 26 °C (299 K)

Greek symbols

γ	surface tension, mN/m
Υ_{LG}	interfacial tension between liquid and gas or vapor, mN/m
Υ_{SG}	interfacial tension between solid and gas or vapor, mN/m
Υ_{SL}	interfacial tension between solid and liquid, mN/m
θ	contact angle, degree
ρ	density, kg/m^3
ϕ	particle volumetric concentration, %

Subscripts

bf	base fluid
bfo	base fluid at a reference temperature
G	vapor
L	liquid
nf	nanofluid

glass surface but not to Teflon or wax. Gaydos and Neuman [3] reported an average contact angle of 109° for distilled water on an FEP type Teflon surface. For water on a hydrophilic solid, the droplet will widely spread out on the solid surface and the contact angle will be close to zero degree, whereas on a hydrophobic solid the water droplet will spread less, such as on a Teflon coated cooking pan. Less strongly hydrophilic solids will have a contact angle up to 90° with water. Present day research has produced surfaces with a contact angle greater than 150° and they are called super hydrophobic surfaces. The contact angle and the wetting phenomenon have attracted a large number of research projects due to their applications in industries; such as in heat transfer with boiling and condensation, oil recovery, lubrication, liquid coating, painting, and spray quenching. Let us outline the importance of contact angle in some applications.

1.1. Influence of contact angle on phase change heat transfer

Both boiling and condensation heat transfers involve liquid and vapor phases. Bubbles and droplets are formed during these processes. The formation of bubbles and droplets is strongly dependent on the surface tension forces, which influence the contact angle at the liquid–vapor–solid interface.

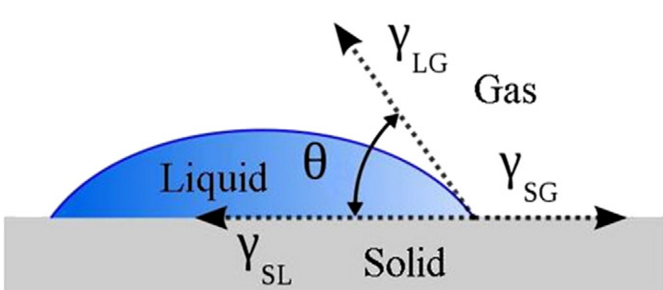

Fig. 1. Contact angle at the liquid–gas–solid interface.

1.1.1. Application in flow boiling in microchannels

Microchannel heat transfer has been an important topic of research in recent years since it promises smaller heat exchangers for the same thermal duty. For flow boiling in microchannels, Kandlikar [4] presents an expression for the critical heat flux (CHF) under pool boiling on a smooth planar surface oriented at an angle of ϕ_1 with horizontal. The CHF depends on the contact angle θ.

$$q_{CHF} = h_{fg}\rho_G^{1/2}\left(\frac{1+\cos\theta}{16}\right)\left[\frac{2}{\pi}+\frac{\pi}{4}(1+\cos\theta)\cos\varphi_1\right]^{1/2} * \left[\gamma g(\rho_L - \rho_G)\right]^{1/4}. \tag{3}$$

Kandlikar introduced a non-dimensional group K_2 which is important for the flow boiling characteristic including the CHF in microchannels. This group $K_{2,CHF}$ for pool boiling is given by

$$K_{2,CHF} = 2\pi\left(\frac{1+\cos\theta}{16}\right)^2\left[\frac{2}{\pi}+\frac{\pi}{4}(1+\cos\theta)\cos\varphi_1\right]. \tag{4}$$

This group, which has a strong dependence on the contact angle θ, is important in CHF analysis during flow boiling in microchannels and minichannels as well. The smaller the contact angle is, the higher the CHF. For wetting liquid ($\theta < 90°$), the liquid is in contact with a greater surface area. So, bubble evaporation will occur under nucleate boiling, achieving the maximum heat flux. For non-wetting liquid ($\theta > 90°$) the liquid is in contact at lesser area of the surface. So, vapor film evaporation will occur achieving lower heat flux due to the high thermal resistance of the vapor film. Therefore, the contact angle of a liquid must be accurately known to evaluate these possibilities.

During the last decade, a new discipline of fluid flow in microchannels and nanochannels has evolved, naming them as microflows and nanoflows. Recently Karniadakis et al. [5] have presented a comprehensive book summarizing the state of the art research on such flows. They have explained surface tension-driven flows in microchannels utilizing thermocapillary and electrocapillary pumping. Since the contact angle and surface tension are closely linked, in order for these new concepts to be extended to the movement of a stream of fluids in such narrow channels, a very accurate knowledge of the contact angle would be essential.

1.1.2. Application in dropwise condensation

For enhancing higher condensation and heat transfer rate in steam condensers and refrigerators, dropwise condensation is preferred to film condensation. This is because, the heat transfer rate under dropwise condensation is an order of magnitude greater than that under film condensation as mentioned in Incropera and DeWitt [6]. A smaller conductive resistance offered by the spherical cap shape droplet to the heat flow between the vapor and the surface makes this possible. To promote dropwise condensation, the surface can be coated with a substance that inhibits wetting. Silicones, Teflons, wax and fatty acids are used as such coating agents. For non-wetting condition, $\theta > 90°$,so droplet condensation and higher heat flux will be achieved. For wetting liquid $\theta < 90°$, so film condensation and lower heat flux will be attained.

1.1.3. Application in oil recovery

In petroleum reservoirs, oil, water or brine and gas coexist inside a matrix of porous rocks made of sandstone, a carbonate or other types of solids. Under the natural condition, one of the liquid phases, oil or water, preferentially wets the rock. Recent research shows that the wetting of the surfaces can be altered in the reservoir by injecting nanofluids. This alteration of wetting can be turned into enhanced oil recovery. Joonaki and Ghanaatian [7] have presented their experimental results of enhanced oil recovery with Al_2O_3, FeO (Iron oxide) and SiO_2 nanoparticles dispersed in propanol. They have reported that these nanofluids changed the rock wettability from water wet to neutral wet and decreased the oil–water interfacial tension. All three nanofluids