Current trends in surface tension and wetting behavior of nanofluids

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ABSTRACT

Nanofluids are recent nanomaterials with improved thermophysical properties that could enhance the efficiency and reliability of heat transfer systems. Relevant properties for heat transfer calculation, thin film flows, droplet impingements or microfluidic are surface tension and wettability. However, to date, the understanding of those properties in nanofluids field is at the beginning compared to transport properties. At this stage, this review focus on the effect of nanoparticles and base fluid nature, temperature, use of surfactant, nanoparticle concentration, size and shape as well on the surface tension and wettability of nanofluids. After the presentation of heat transfer processes involving the influence of surface tension and wettability, this paper is organized according to the nature of the nanoparticles dealing with oxide, carbon-based and metallic nanofluids as well as unusual or less considered nature of nanoparticles. The factors affecting the surface tension of nanofluids are relatively well identified, but concentration and surfactant effects present some inconsistent outcomes. In any case, the dispersion of nanoparticles have an effect on the surface tension of base fluid significantly lower than that on transport properties. Based on results available in the literature and existing empirical correlations, a comprehensive assessment, challenges and future works are suggested.

1. Introduction

The surface tension (ST) of thermal fluids is of great importance when analyzing the performance of thermal systems since this physical property influences the surface wettability and bubble growth. Hence, ST is, together with the vaporization latent heat and the density difference between liquid and vapor phases, the most important parameters in order to describe boiling and condensation processes [1].

In a non-dimensional analysis of boiling heat transfer flows, ST appears in the Bond number (Bo), which represents the ratio of the buoyancy forces to the surface tension forces. If the Bo value is high, the working fluid is supposed to boil vigorously [2]. Hence, a reduction in ST is expected to enhance the boiling flow heat transfer performance. ST is also present in most of the correlations proposed in literature for nucleate pool boiling [3], particularly at critical heat flux conditions [4,5]. According to these equations, nucleate boiling heat flux can be enhanced by reducing surface tension [6]. Regarding external forced boiling such as in a fire tube boiler, Lienhard and Eichhorn [7] developed expressions for low and high velocity flows. In both situations, a reduction in ST leads to an increase in Weber number and a diminution

of convective heat flux [6]. Recently, Fang et al. [8] and Ciloglu and Bolukbasi [9] reviewed main literature outcomes concerning nanofluid performance under flow boiling the former and nucleate boiling the later. Both works underline the importance of ST to understand flow patterns and bubble dynamics under boiling. Authors such as Vafei et al. [10] pointed out that the addition of nanoparticles can play even a double role. Thus, suspended particles modify bubble dynamics significantly by varying contact angles, departure bubble volume, and frequency, while nanoparticle deposited on the heating surface modify surface wettability and reduce thermal resistance of evaporator and condenser.

Heat pipes are heat-transfer devices currently used in cooling management of electronics and computers. These capillary structures consist of a tube closed at both ends that combines the principles of high thermal conductivity and phase transition to effectively transfer thermal energy between two solid interfaces when subjected to a temperature difference [11]. The capillary effect consequence of the surface tension of the working fluid can lead to a liquid transference from the condenser to evaporator, which in turn can influence the increase in thermal performance of heat pipes. Correlations for predicting

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Nomenclature

Abbreviations

ST	Surface tension	PDMS	Polydimethylsiloxane
IT	Interfacial tension	PEG	Polyethylene glycol
W	Wetting behavior or Wettability	PTFE	Polytetrafluoroethylene
CA	Contact Angle	PVP	Polyvinylpyrrolidone
CMC	Critical micelle concentration	SDS	Sodium dodecyl sulfate
CTAB	Cetyltrimethyl ammonium bromide	SDBS	Sodium dodecyl benzene sulfonate
DIW	Distilled water	T	Temperature
DG	Diethylene glycol	TEG	Triethylene glycol
DTAB	Dodecyltrimethyl-ammonium bromide	ϕ	Nanoparticle loading (in wt%, vol%, g/l or ppm)
EG	Ethylene glycol	γ	Surface tension
G	Graphene	np	nanoparticle
GO	Graphene oxide	bf	base fluid
		nf	nanofluid
		$\uparrow$	Increase
		$\downarrow$	Decrease
		$\rightarrow$	Constant

the heat transfer of heat pipes such as that proposed by Kim and Peterson [12] require the knowledge of surface tension. There, Weber number is used to explain the counter-current interactions between free surface of liquid film and vapor flows inside the operating heat pipe, and provides a convenient measure of the likelihood of liquid entrainment [2].

Two-phase closed thermosiphons (TPCT) are thermodynamically similar to wicked heat pipes with gravity-assisted liquid-vapor flows. The maximum heat flux inside the evaporator of a thermosiphon can be expressed in a dimensionless way through Kutateladze number [13], which is usually correlated as a function of Bond number [2,14]. Like with the rest of heat pipes, the main research areas to enhance the performance of TPCTs are focused on the necessity of a better wick development to minimize entrainment and optimizing the fluid design [2]. In this sense, it is well known that reductions in ST can improve TPCT performance [15]. Liu and Li [16] and Gupta et al. [17] reviewed

and summarized previous research on heat pipes using nanofluids as working fluids. The majority of nanofluid studies showed a reduction in thermal resistance of heat pipes and thermosiphons with the addition of nanoparticles to the working fluid. Most authors attributed improvements in thermal performance and operating range to modifications in thermal conductivity but also in surface tension, liquid density and latent heat of vaporization.

In recent years, microfluidics and minifluidics have raised increasing attention in heat transfer field due to current trend towards component miniaturization in a wide range of industrial applications. In particular, flow boiling in microchannels has been proposed as a promising cooling method, due to the possibility of achieving very high heat transfer rates with small variations in the surface temperature [18]. According to the classification proposed by Cheng et al. [19] for two-phase channels, Bond number must be below 0.05 for the flow system to be considered as microchannel. These low Bo values indicate

Table 1
Thermal configurations and applications involving surface tension influence.

Type of heat and mass transfer application	Main heat and mass transfer governing equations depending on surface tension	Parameter involving the surface tension	Influence of surface tension
Boiling heat transfer	$Nu = \frac{h \cdot L}{k} = f\left[\frac{\rho \cdot g \cdot (\rho_l - \rho_v) \cdot L^3}{\mu^2}; Pr = \frac{\mu \cdot c_p}{k}; Ja = \frac{\Delta T \cdot c_p}{h_{fg}}; Bo = \frac{g \cdot (\rho_l - \rho_v) \cdot L^2}{\gamma}\right]$ Where Nusselt (Nu), Prandl (Pr), Jacob (Ja) and Bond (Bo) numbers depend on the characteristic length (L), thermal conductivity (k), density (ρ), viscosity (μ), isobaric heat capacity (c_p), excess temperature (ΔT), latent heat of vaporization (h_{fg}), surface tension (γ) and acceleration due to gravity (g). Subscripts stand for liquid (l) and vapor (v).	Heat transfer coefficient (h) and Bond number (Bo) [1]	Bo $\uparrow$ and h $\uparrow$ if ST $\downarrow$
Nucleate pool boiling, Critical heat flux	$q'' = \mu_l \cdot h_{fg} \cdot \left(\frac{g \cdot (\rho_l - \rho_v)}{\gamma}\right)^{1/2} \cdot \left(\frac{c_{p,l} \Delta T}{C_{s,f} \cdot h_{fg} \cdot Pr_l^n}\right)^3$ Where $C_{s,f}$ coefficient and n exponent depend on the solid–liquid combination. $q''_{max} = C \cdot h_{fg} \cdot \rho_v \cdot \left(\frac{\gamma \cdot g \cdot (\rho_l - \rho_v)}{\rho_v^2}\right)^{1/4}$ Where C is a constant depending on heated surface geometry.	Critical heat flux for nucleate boiling (q'') [4,5]	q'' $\uparrow$ if ST $\downarrow$
External flow convection	Low velocity: $\frac{q''_{max}}{\rho_v \cdot h_{fg} \cdot V} = \frac{1}{\pi} \cdot \left(1 + \left(\frac{4}{We_D}\right)^{1/3}\right)$ High velocity: $\frac{q''_{max}}{\rho_v \cdot h_{fg} \cdot V} = \frac{(\rho_l / \rho_v)^{3/4}}{169 \cdot \pi} + \frac{(\rho_l / \rho_v)^{1/2}}{19.2 \cdot \pi \cdot We^{1/3}}$ Where $We = (\rho_v \cdot V^2 \cdot D)/\gamma$ is the Weber number, V is the liquid velocity and D is the diameter.	Critical heat flux for external convection boiling (q'') and Weber number (We) [7]	We $\uparrow$ and q'' $\downarrow$ if ST $\downarrow$
Flow boiling in Microchannels	$K_2 = \left(\frac{q''}{h_{fg}}\right)^2 \cdot \frac{D}{\rho_v \cdot \gamma}$; $Ca = \frac{\mu \cdot V}{\gamma}$	Kandlikar (K_2) and capillary number (Ca) [23]	Ca $\uparrow$ if ST $\downarrow$
Heat pipes	$We_{critical} = \frac{\rho_v \cdot v^2 \cdot z}{2 \cdot \pi \cdot \sigma} = 10^{-1.163} \cdot N_{vi}^{-0.744} \cdot \left(\frac{\lambda_c}{d_1}\right)^{-0.509} \cdot \left(\frac{D_h}{d_2}\right)^{0.276}$ Where z is a dimension characterising the vapor liquid surface, v is the vapor velocity, N_{vi} is the dimensionless viscosity number, λ_c is the critical wavelength, d_1 is the mesh wire spacing, d_2 is the wire thickness and D_h is the equivalent diameter of the vapor space.	Weber number (We) [12]	We $\uparrow$ if ST $\downarrow$
Thermosiphons	$Ku = \frac{q_{co}}{(\Delta h_{lv} \cdot \rho_v^{0.5} \cdot (\sigma \cdot g \cdot (\rho_l - \rho_v)^{0.25}))}$	Maximum heat flux (q_{co}) and Kutateladze number (Ku) [13]	Ku $\uparrow$, q_{co} $\downarrow$ if ST $\downarrow$