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Review of pool boiling enhancement with additives and nanofluids

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ABSTRACT

Enhancement of nucleate pool boiling by modifying fluid properties has drawn considerable attention in recent years. This paper provides a comprehensive review of published literature concerning enhancement methodologies of surfactant and polymer additives, and nanofluids. Each method is discussed in detail in terms of measured impact on the nucleate boiling heat transfer coefficient and critical heat flux (CHF), mechanisms proposed for any heat transfer enhancement, and predictive models. It is shown that adding surfactant to base liquid shifts the nucleate boiling region of the boiling curve towards lower surface superheats, thereby promoting earlier boiling incipience and increasing the nucleate boiling heat transfer coefficient, but the heat transfer merits of polymer addition are polymer specific. Despite significant enhancement in CHF with most nanofluids, there are many contradictory findings concerning influence of nanofluids on nucleate boiling heat transfer coefficient. These contradictions are the result of many complex influences of base liquid, nanoparticles, and initial surface roughness. Despite the potential heat transfer benefits of nanofluids, there are several serious practical concerns that must be considered carefully before deploying nanofluids in practical cooling applications.

1. Introduction

1.1. Pool boiling applications

Heat transfer processes are essential to daily operation in virtually every modern industry. Most of these processes employ a primary fluid to acquire, transport, and reject the heat, with liquids being preferred because of their superior thermophysical properties. This is especially the case when the liquid undergoes phase change (by boiling and/or condensation), thus capitalization on both its sensible and latent heat [1,2]. In fact, phase change processes are prevalent in a vast number of applications. They include cooling of nuclear reactor cores, fusion reactor blankets, particle accelerator targets, magnetohydrodynamic (MHD) electrode walls, supercomputers and data centers, aircraft and spacecraft avionics, hybrid vehicle power electronics, laser and microwave directed energy weapon electronics, advanced radars, X-ray medical devices, engine heads, and turbine engine blades [3]. Phase change cooling is also crucial for quenching of metal alloy parts in pursuit of superior mechanical properties.

Boiling processes can be implemented in a variety of schemes [4], including pool boiling [5,6], macro/mini/micro-channel flow boiling [7], jet-impingement [8], and spray [9,10], as well as hybrid configurations combing two or more of these schemes [11]. Pool boiling is especially popular in many industries by virtue of its passive (pump-free) operation as well as both simplicity and cost effectiveness [12]. But, in the absence of a pump to increase coolant flow velocity in order to enhance heat transfer rate, other methods are necessary to enhance pool boiling by modifying thermophysical properties of the liquid itself, modifying the boiling surface, or both.

One application for which such enhancement might be crucial is thermal management in space applications. Here, absence of gravity is known to greatly compromise boiling heat transfer effectiveness by triggering critical heat flux (CHF) at unusually low heat flux values [13–16]. Without additional enhancement, pool boiling is unlikely to pose a viable cooling option for these applications. A key merit in the use of nanoparticles to enhance nucleate pool boiling in microgravity is weak tendency for surface sedimentation, which is often reported as a key concern during long-term exposure of the heating surface to nucleate boiling in Earth gravity.

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Nomenclature

c_p	specific heat at constant pressure
g	gravitational acceleration
h	heat transfer coefficient
h_{fg}	latent heat of vaporization
k	thermal conductivity; coefficient in Eq. (9)
q''	heat flux
q''_{CHF}	critical heat flux
r	bubble radius
R_a	average surface roughness
T	temperature
t	time
ΔT_{sat}	surface superheat
υ_{fg}	liquid-vapor specific volume difference

Greek symbols

α	contact angle
θ	orientation angle
λ_{bare}	wavelength in Zuber's model
λ_m	modified wavelength for nanofluids
μ	dynamic viscosity
υ	kinematic viscosity
ρ	density
σ	surface tension
ϕ	concentration

Subscripts

bare	bare surface
f	liquid
g	vapor
i	incipience
nf	nanofluid
sat	saturation
vol	volume
w	wall/solid
wt	weight

1.2. Pool boiling and quench curves

Before discussing the different pool boiling enhancement methods, it is crucial to relate these methods to specific boiling regimes. These regimes are identified with the aid of two types of performance curves: the boiling curve, Fig. 1(a), and the quench curve, Fig. 1(b). The boiling curve depicts variations of wall heat flux with wall-to-saturation temperature difference (wall superheat). This curve is highly effective at identifying the different heat transfer regimes prevalent at different levels of superheat: (a) single-phase liquid cooling, corresponding to low superheats, (b) nucleate boiling, dominated by bubble nucleation, growth, and departure along the surface, (c) transition boiling, where portions of the wall incur bubble nucleation while others are blanketed with vapor, and (d) film boiling, corresponding to high wall superheats causing vapor blanketing over the entire surface [12]. These four regimes are demarcated by three important transition points: (i) onset of boiling (incipient boiling) corresponding to first bubble formation on the wall, (ii) critical heat flux (CHF), where bubble nucleation in nucleate boiling is replaced by localized vapor blankets merging together across the surface, and (iii) minimum heat flux (Leidenfrost point), corresponding to onset of breakup of the continuous vapor blanket in film boiling when decreasing the wall superheat. These transition points mark profound changes in heat transfer effectiveness between the different regimes, with the nucleate boiling regime providing the highest heat transfer coefficients and the film boiling regime the lowest.

On the other hand, the quench curve, Fig. 1(b), is a better representation of the variations in cooling rate encountered when the surface is quenched from initially high temperature corresponding to film boiling to near room temperature. Unlike the boiling curve, which is a measure of only surface thermal interactions, the quench curve also accounts for thermal mass of the quenched part. The large variations in heat transfer coefficient associated with the

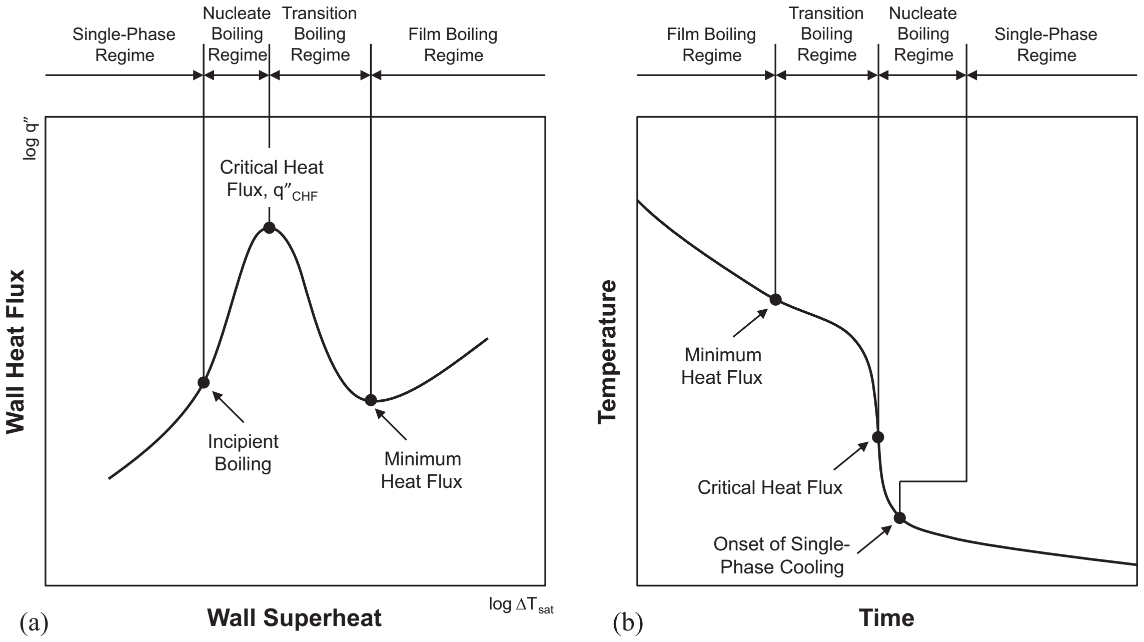

Fig. 1. (a) Pool boiling curve and (b) quench curve.