



Wettability-independent critical heat flux during boiling crisis in foaming solutions

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ABSTRACT

We present the first experimental study of surface wettability-independent critical heat flux (CHF) during boiling crisis with foaming solutions. Foaming solution refers to those aqueous surfactant solutions, which are very effective in avoiding bubble coalescence and form vapor foam. The slowly rising small bubbles in the foam crowd the heater surface to inhibit rewetting and trigger boiling crisis. Similar to the typical relation between the terminal velocity and the bubble size, we observe a power law exponent of half between the CHF and the bubble size. Such a behavior suggests that the ability of buoyancy to remove bubble swarm away from the heater surface dictates the CHF during boiling with foaming solutions. Resulting premature dryout not only reduces CHF significantly in comparison to boiling with pure water but also renders the effect of wettability improvements from micro-/nano- texturing inconsequential to CHF enhancement. Terminal velocity of the rising bubbles is estimated to model the maximum vapor-removal capacity and successfully predict the CHF over a wide range of concentrations. We further show that weakly foaming surfactants, or, the strongly foaming surfactants, but at lower concentrations, behave similar to water wherein they form large bubbles and wettability improvements via surface modifications exhibit CHF enhancements. The physical insights gained in this study can now be used to devise strategies for CHF enhancement with aqueous surfactant solutions.

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1. Introduction

Boiling heat transfer is fundamental to many household processes and industrial applications such as cooking, water purification, thermoelectric power plant, chemical and petrochemical processing, thermal management of electronic equipment, refrigeration and air conditioning, and cryogenic fuel storage [1–4]. The ebullition cycle, which is a combination of the nucleation of the vapor bubble, its growth, departure, and rewetting of the heater surface in a cyclic manner governs the heat transfer during boiling. Boiling crisis occurs at relatively high heat fluxes when the nucleating bubbles coalesce to form a large vapor blanket which covers the heated surface. Vapor blanket interrupts rewetting of the heater surface with fresh liquid, forcing dryout. Negligible contact between the boiling fluid and the heated surface induces thermal runaway, i.e., an abrupt and uncontrollable rise in temperature to unacceptable limits. The corresponding heat flux is known as the critical heat flux (CHF), and is the upper limit of safe and reliable operations during boiling.

The value of CHF with a given fluid depends strongly on the heater surface properties [5,6] such as surface chemistry, roughness, and porosity, all of which in turn dictate the wettability [7]. It is a common knowledge that any modification in the heater surface, which affects wettability, also alters the value of CHF. Any improvement in wettability through incorporation of roughness/porosity features facilitates easy rewetting of the heater surface and is typically used to delay the boiling crisis, i.e., enhance the CHF. Advances in micro-/nano-fabrication technologies [5,6,8] have enabled researchers to manipulate roughness via surface texture and chemistry to fabricate surface coatings which extend the limits of wettability to further extremes. Accordingly, micro-/nano-scale textures/structures such as microchannels, micropillars, nanopillars, nanowires, hierarchical structures, and nanoparticle coatings [5,6,9,10] have been successfully employed for CHF enhancement beyond the typical limits on machined/polished engineering surfaces [11,12].

Conversely, various types of additives are also used to enhance boiling heat transfer [13]. In this regard, the use of surfactant additives in the boiling fluid is a simple and widely used technique for the enhancement of heat transfer coefficient (HTC) due to the combined effect of increase in bubble departure frequency [14–16] and the active nucleation site density [17]. For example, Wasekar and

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Nomenclature

A	surface area (cm^2)		
A_R	area ratio		
C	concentration of surfactant in bulk liquid (mol/l)		
C_d	drag coefficient of bubble in swarm		
D	bubble diameter (m)		
D^*	diffusion coefficient (m^2/s)		
dT/dx	temperature gradient (K/m)		
g	gravitational acceleration (m/s^2)		
h	heat transfer coefficient ($\text{kW}/\text{m}^2\text{K}$)		
h'	adsorption depth (m)		
h_{lv}	latent heat of vaporization (J/kg)		
k	thermal Conductivity (W/mK)		
q''	heat flux (kW/m^2)		
q''_{exp}	experimental heat flux (kW/m^2)		
q''_{CHF}	critical heat flux (kW/m^2)		
$q''_{\text{CHF,exp}}$	experimental critical heat flux (kW/m^2)		
r	roughness factor		
Re	reynolds number		
T	temperature ($^{\circ}\text{C}$)		
T_w	surface temperature ($^{\circ}\text{C}$)		
T_{sat}	saturation temperature at atmospheric pressure ($^{\circ}\text{C}$)		
U	superficial velocity of steam (m/s)		
U_T	terminal velocity (m/s)		
$U_{T,W}$	terminal velocity of bubble in water (m/s)		
$U_{T,S}$	terminal velocity of bubble in surfactant solution (m/s)		
ΔT_{sup}	wall superheat, ($T_w - T_{\text{sat}}$) ($^{\circ}\text{C}$)		
ΔT_{sub}	subcooling, ($T_{\text{sat}} - T_l$) ($^{\circ}\text{C}$)		
		<i>Greek symbols</i>	
		Γ	surface concentration (mol/m^2)
		Γ_m	surface concentration at CMC (mol/m^2)
		τ_D	time-scale of diffusion (ms)
		σ	surface-tension (N/m)
		ρ	density (kg/m^3)
		<i>Subscripts</i>	
		sub	subcooling
		sup	superheat
		surf	surfactant
		l	liquid
		v	vapor
		w	water
		n	nanostructure
		μ	microstructure
		trans	transition
		<i>Abbreviation</i>	
		CHF	critical heat flux
		HTC	heat transfer coefficient
		ppm	parts per million
		CMC	critical micelle concentration

Manglik (2002) [14] performed pool boiling experiments with water and aqueous solutions of various ionic and non-ionic surfactants, including SDS and Triton X-100. The nucleation site density and the bubble departure frequency were observed to increase with the addition of surfactants. Significant enhancement in HTC was reported in comparison to pure water. The maximum enhancement in HTC was observed around the critical micelle concentration (CMC). The trend in HTC was linked to the ability of surfactants to reduce the surface-tension value based on their mobility, which was further related with their molecular weight. Zhang and Manglik (2005) [15] also focused on the reduction in surface-tension along with the improved wettability to explain the enhancement in HTC with various aqueous surfactant solutions including SDS. Hetsroni et al. (2001) [16] performed pool boiling study with aqueous solution of Habon G (surfactant) and suggested that the reduction in surface-tension was the important parameter which affects the boiling heat transfer performance.

Interestingly, most of the above listed studies with aqueous surfactant solutions report HTC trends only in the low heat flux regime much below the CHF [15,16]. A few studies which deal with the high heat flux generally report a substantial reduction in CHF in comparison to pure water (see Table 1, CHF_{surf}/CHF_w, S.N. 1–3). For example, Wu et al. (1994) [18] estimated the CHF during saturated pool boiling using quenching method for aqueous SLS (Sodium Lauryl Sulphate or SDS) solution at various concentrations. The CHF was reported to decrease significantly with the addition of surfactant in pure water. Moreover, increase in the concentration of surfactant further decreased the value of CHF. Similarly, Kathiravan et al. [19,20] also reported significant deterioration in CHF during boiling with aqueous SDS solution in comparison to boiling with pure water. However, the mechanism associated with the degradation in CHF was not explained. While the reduction in surface-tension in comparison to pure water due to the addition of surfactants may be responsible for the par-

tial decrease in CHF, a quick analysis of the CHF data present in these studies suggest that the deterioration with respect to water does not follow the relation $q''_{\text{CHF}} \propto \sigma^{1/4}$ [18], as suggested by most models of CHF in literature [11,12]. This suggests that the surface-tension reduction in comparison to pure water alone cannot explain the degradation in CHF during boiling with aqueous surfactant solutions.

Please note that Table 1 also lists many studies (S.N. 4–6) which report an insignificant change or instead an enhancement in CHF with the addition of surfactants. However, all of these studies have been performed on heated wires much smaller than the capillary length of water (or water with aqueous surfactant solutions). It is well known that boiling in this regime deviates from the classical boiling behavior [21,22]. Surface-tension dominates over buoyancy and CHF increases upon decreasing the bubble/heater size [23–26]. Hence, the CHF values reported in these studies cannot be compared with those on a large heater surface where buoyancy dominates boiling and the CHF values with aqueous surfactant solutions are always smaller than the CHF values with pure water on a similar heater.

The studies in literature summarized above clearly highlight that the HTC enhancements with surfactants cannot be realized at high heat fluxes due to significant deterioration in CHF (excluding the data for boiling on wires) in comparison to pure water. However, some of the recent studies demonstrate that surfactants facilitate a completely passive bubble departure on an inverted heater against the opposing forces of buoyancy and surface-tension [30,31]. Using this bubble departure mechanism, it was further shown that aqueous surfactant solutions have the potential for simultaneous enhancement of CHF and HTC in the absence of buoyancy induced bubble departure [30,31], generally observed on an inverted heater in earth gravity or during boiling in micro-gravity conditions. Surprisingly, similar attempts at simultaneous HTC and CHF enhancements during boiling with aqueous

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