Experimental investigation of transient critical heat flux of water-based zinc–oxide nanofluids

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ABSTRACT

Pool boiling experiments were conducted for sandblasted stainless steel (grade 316) plate heaters submerged in deionized (DI) water and water-based zinc–oxide nanofluid, for transient heat flux conditions with power through the heaters increasing quadratically with time. Heat flux in the experiments was increased from zero to CHF in short time frames of 1, 10 and 100 s. Consistent with previous studies, transient CHF for DI water was higher than steady state CHF, and CHF increased with decreasing duration of the transient. Additionally, it was observed that for nanofluid tests, a porous and hydrophilic nanoparticle layer started to deposit on the heater surface in short time frames of 10 and 100 s, and this layer was responsible for the enhanced CHF compared to DI water. However, for the 1 s tests, nanoparticle deposition did not occur and consequently the CHF was not enhanced. Finally, experiments with heaters precoated with nanoparticles were performed and it was found that CHF was enhanced for all transient durations down to 1 s, establishing firmly that the CHF enhancement occurs due to surface modifications by the deposited nanoparticles, and not by nanoparticles suspended in solution.

1. Introduction

Nucleate boiling is a very efficient mode of heat transfer owing to the large energy required to realize the phase change from liquid to vapor. Therefore, several important industrial applications utilize nucleate boiling to remove large heat fluxes from hot surfaces. These include nuclear reactors, miniature electronic devices, refrigeration and cryogenic systems, chemical and thermal reactors, among others. However, it is well known that there exists a critical value of the heat flux at which the heat transfer mechanism changes from the highly efficient nucleate boiling to extremely inefficient film boiling. This limiting heat flux is called Critical Heat Flux (CHF). The deterioration in the process of heat removal from the hot surface, due to the initiation of film boiling, can cause rapid excursions in the temperature of the heat source which can lead to destruction of the boiling surface. Therefore, in most applications of boiling, the system is required to operate at power levels below that corresponding to CHF. As such, there is considerable interest in increasing CHF since, everything else being constant, a higher value of CHF allows for higher power density in thermal systems, which in turn makes these systems more compact and ultimately more economic. One way to increase CHF is to suspend a small amount of nanoparticles in the base fluid to form a suspension called nanofluid [1,2]. The main objective of this paper is to report on an experimental study that examined the effect of nanofluids on CHF behavior for rapidly increasing heat flux excursions, with excursion times less than 100 s. The structure of the paper is as follows: Section 3 reviews the literature on nanofluids and transient CHF; Section 3 describes the preparation and characterization of the nanofluids used in the experiments; the experimental procedure is described in Section 4. The results are summarized in Section 5, followed by the discussion in Section 6 and conclusions in Section 7.

2. Literature review

2.1. Nanofluids

Several techniques to enhance the CHF have been explored. According to Rohsenow et al. [3] they can be classified into *active* (requiring external changes to the heater) or *passive* (requiring no external changes to the heater) methods. Typical active approaches include vibration of the heated surface or the cooling fluid (to increase the bubble departure frequency), heater rotation (to promote bubble departure from and liquid deposition onto the heater surface) and applying an external electric field (to facilitate the bubble departure from the surface by dielectrophoretic force),

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Nomenclature

α	temperature coefficient of resistivity [Ω/Ω °C]		ρ	density [kg/m^3]
A_{ht}	area of heat transfer[m^2]		R	resistance [Ω]
CHF	critical heat flux [kW/m^2]		R_{100}	resistance at 100 °C[Ω]
c_p	specific heat capacity [J/kg °C]		R_a	average surface roughness [μm]
DAS	data acquisition system		t_0	ramp time for current for transient tests [s]
HTC	heat transfer coefficient [kW/m^2 °C]		T_{bulk}	bulk heater temperature [°C]
I	current [A]		ΔV	potential drop across heater [V]
PBF	pool boiling facility			
q''	heat flux [kW/m^2]			

and passive approaches include coating the surface with porous coatings (to increase the number of active nucleation sites) and oxidation or selective fouling of heater surface (to increase surface hydrophilicity) [4]. A recent passive approach that has garnered increased attention worldwide is to create a colloidal suspension of solid nanoparticles in water or other base fluid, called nanofluids [1,2]. There are various materials of choice for the dispersed nanoparticles-chemically stable metals (such as Cu, Au and Ag), metal oxides (such as Al$_2$O$_3$, SiO$_2$ and ZrO$_2$) and different forms of carbon (such as diamond, graphite and fullerene). Boiling tests have shown these engineered nanofluid coolants to have a significantly higher CHF (generally, an enhancement ranging from 20% to more than 100%) compared to water. You et al. were the first researchers to observe a considerable CHF enhancement in alumina nanofluids [5]. Since then, nanofluid boiling has generated a lot of curiosity and efforts to understand the underlying CHF enhancement mechanism. Researchers also investigated changes of the heat transfer coefficient (HTC) for nanofluids compared to water. The findings from the literature can be summarized as follows:

- All researchers observed deposition of a layer of nanoparticles on the boiling surface during the course of nanofluids boiling. According to common consensus by researchers [7–12], this nanoparticle deposition layer is the primary mechanism for CHF enhancement, as it changes the porosity and the hydrophilicity of the surface, altering the dynamics of the three phase interface at the heater surface.
- Most of the studies report significant CHF enhancement (up to 200%) with nanofluids compared to water [5–18].
- Even relatively low concentrations (<1% by volume) of nanoparticles are capable to enhance CHF.
- Researchers have reported contradicting findings on the effect of nanofluid on HTC. While some studies have shown an enhancement in HTC for nanofluids compared to water [12,13,19–21], others show deterioration [7,14,22–24] and few document no effect of suspended nanoparticles on HTC [5,6,8,10,11].

2.2. Transient CHF

It is well documented that the value of the transient CHF can be significantly different from the steady state CHF value [25–33]. Most of the studies reported are for an exponentially increasing volumetric power input given by $Q = Q_0 e^{t/\tau}$, where Q_0 is the initial power level per unit volume in the heater and τ is the time constant for the transient. There have been several attempts to understand the mechanism for transitions from conduction, natural convection and nucleate boiling regimes to film boiling regime, due to exponentially increasing heat inputs with various fluids, such as water, and highly wetting fluids such as liquid nitrogen, liquid helium and ethanol [25–33]. Sakurai and Shiotsu, first,

suggested that the boiling curve for transient tests is slightly different from that of steady heat flux tests [26,27]. Sakurai et al. also observed that for a fixed heat flux value, HTC for transient tests after boiling initiation was lower than that for steady state tests [29]. This was explained as follows: As the heat input to the heater is increased exponentially, its surface temperature also increases. Due to an increase in surface temperature, unflooded cavities with entrapped air get activated, leading to nucleation from those cavities. Upon further increase in wall temperature due to an increase in heat input, even more unflooded cavities are activated, leading to stronger bubble nucleation. Eventually at one level of wall temperature, even the cavities that are originally flooded with fluid get activated due to bubbles originating from neighboring cavities. At this point, due to the activation of a very large number of cavities, the heater wall temperature starts to decrease and the number of activated cavities again decreases. Thus, the amount of nucleation sites also drops. Hence, compared to steady state experiments, the number of active cavities at a given heat flux after the inception of boiling is lower for transient tests. This phenomena leads to a lower HTC for transient tests, compared to steady boiling tests. In other words, there is a time lag associated with the activation of all nucleation sites for transient tests, compared to steady heat flux tests. Sakurai et al. conducted investigations of the mechanism to film boiling during exponentially increasing heat inputs on a solid surface, for liquid nitrogen, water and ethanol [30,31]. For liquid nitrogen and ethanol (completely wetting fluids), they observed that a direct transition to film boiling happened from the non-boiling regime, independent of the exponential period. They suggested a new mechanism responsible for the direct transition to film boiling, and backed it by conducting photographic investigations of the solid/fluid interface. This was called Heterogeneous Spontaneous Nucleation (HSN). HSN is an explosive-process, where nucleation occurs from all cavities (flooded or unflooded) at a particular rate of increase of surface superheat. The surface temperature and the rate of increase of surface superheat, where HSN occurs, depend on the time constant of the transient. The faster the transient, the higher the HSN superheat required. Once initiated, HSN proceeds very rapidly and results in complete evaporation of the liquid in contact with the surface, thus covering the entire heater surface with a vapor film.

All the experimental efforts on nanofluids CHF to date were done for steady state conditions, i.e. the heat flux in experiments was increased in small incremental steps and was held constant at each step for a certain amount of time to allow for the achievement of a steady state. The duration of 'steady state' experiments typically is from several minutes to several hours. Thus, in these experiments, the nanoparticles have ample time to deposit on the surface and affect boiling behavior and hence the CHF. However, during certain reactivity-initiated accident scenarios in nuclear reactors, such as the rod ejection event, a very rapid power excursion in the fuel can occur, as fast as 0.25–0.50 s [34,35].