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Pool boiling of nanofluids: Comprehensive review of existing data and limited new data

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ABSTRACT

Nanofluid pool boiling experimental studies have shown mixed results. Recent literature is reviewed and compared here. It is demonstrated here that experiments can be fit to the traditional Rohsenow correlation by changing the surface constant, C_{sf}. Therefore, this study suggests surface conditions are responsible for varying results. Some limited new experimental data are reported for Al_2O_3/H_2O nanofluids using the hot wire method. Relative to the baseline of pure water, boiling incipience occurs 2–3 °C earlier, heat transfer is enhanced 25–40%, but sub-cooled boiling deteriorates. These results are essentially in agreement with most earlier studies showing enhancement [S.K. Das, N. Putra, W. Roetzel, Pool boiling of nanofluids on horizontal narrow tubes, Int. J. Multiphase Flow 29 (8) (2003) 1237–1247; D. Wen, Y. Ding, Experimental investigation into the pool boiling heat transfer of aqueous based c-alumina nanofluids, J. Nanoparticle Res. 7 (2005) 265–274; S. Witharana, Boiling of refrigerants on enhanced surfaces and boiling of nanofluids, Ph.D. thesis, The Royal Institute of Technology, 2003; S.M. You, J.H. Kim, K.H. Kim, Effect of nanoparticles on critical heat flux of water in pool boiling heat transfer, Appl. Phys. Lett. 83 (2003) 3374–3376].

1. Introduction

In the past two decades an increasing amount of research has been conducted in nanoscale science. One promising subset of this field involves adding nanoparticles to a conventional base liquid. The term *nanofluid* was proposed in 1995 by Choi [1] to describe this combination. Since then, the main thrust of nanofluid research has been to develop better heat transfer fluids. The promise of nanofluids stems from the fact that at relatively small particle loading, typically <1% by volume, significant enhancement in thermal transport may be possible. Also, due to the small size of the individual particles, a stable nanofluid would *not*, ideally, foul system pumps or plumbing. Therefore, commercial nanofluids have the potential to give significant improvements in efficiency and/or performance without significantly altering existing systems.

Since research on this topic began, several studies have noticed increases in effective thermal conductivity [1–9] – up to 60% with copper oxide (CuO) nanoparticles in water [4]. Following, and alongside, this work several researchers have investigated convective heat transfer. Unfortunately, characterization of the heat transfer coefficient has led to some disagreement over whether enhancement is even possible in the literature [10–19]. Results range from an increase of >30% (alumina (Al_2O_3) and copper oxide (CuO)/H_2O nanofluids under *forced* convection) [11] to "a systematic and definite deterioration" for Al_2O_3 and CuO/H_2O nanofluids under *natural* convection [14].

Most recently – in the past 6–7 years – researchers have considered the possibility of enhanced boiling heat transfer in nanofluids [19–41]. Results of these tests also seem to contradict one another in the literature. It seems, in pool boiling studies in general, experimental results are very dependent upon the specific test conditions. Disagreement for nanofluid boiling is logical, since there are so many variables involved: nanofluid type, heater material, surfactant use, heater geometry, saturation pressure, and measurement equipment – to name a few. Indeed, even simple pool boiling data with pure fluids show significant scatter and hysteresis [34].

The aim of this study is to review the body of experimental work on nanofluid pool boiling and to compare these results with some limited new data of Al_2O_3/water nanofluids. This study will also try to present some plausible explanations for contradictions in the pool boiling literature. In order to do so we must first review the literature on nanofluid pool boiling.

2. Review of recent research

As mentioned above, there has been considerable disagreement over the value of using nanofluids during pool boiling. Interest-

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Nomenclature

c	specific heat (J kg^{-1} K^{-1})
C	correlation constant
g	gravitational constant (m s^{-1})
h	enthalpy (J kg^{-1})
I	current (A)
Pr	Prandtl number
R	electrical resistance (Ω)
T	temperature (K)
V	voltage (V)

Greek symbols

α	coefficient of resistance (°C^{-1})
Δ	change
η	efficiency
μ	dynamic viscosity (kg m^{-1} s^{-1})
σ	surface tension (N/m)
Ω	ohms

Subscripts

c	cold
f	fluid
fg	vaporization (fluid to gas)
h	hot
m	measured
pl	constant pressure liquid
PS	power supply
$ref.$	reference
$sat.$	saturation temperature
sf	surface
v	volume
w	wall
w	wire

ingly, at the time of writing this article, there is a nearly even three-way split in experimental results. Seven studies have shown enhancement [28,32,33,35–37], seven have shown degradation [19,21,23,24,29,39,41], and five saw little or both enhancement and degradation [20,25,31,34,38]. Table 1 summarizes the literature results. Note: Unless otherwise stated, enhancement or degradation is relative to pure water – the conventional base fluid.

2.1. Literature showing enhancement

The papers showing enhancement give an average enhancement ranging from 30–60% higher heat transfer during nucleate boiling. Liu et al. [28] used copper oxide (CuO) particles in an attempt to increase the effectiveness of the evaporator of a miniature flat heat pipe. These authors tested nanofluids on smooth micro-grooved surfaces at different pressures. They found significant enhancements (especially at low pressures) until the mass concentration exceeded 1% – after which enhancement decreased. Also, in this same study, a thin layer of ‘porous’ nanoparticles was found to be deposited on the heater surface after testing. Shi et al. [32] conducted experiments with iron (Fe) and alumina (Al_2O_3) nanoparticles boiled on a Cu block. The authors concluded that Fe particles showed more enhancement than Al_2O_3 particles and that enhancement was mostly due to increases in thermal conductivity and lowered surface tension. It should also be noted that the authors saw some particle deposition. Tu et al. [33] tested Al_2O_3 nanofluids on a ‘nanoscopically smooth’ vapor-deposited heating surface. Limited data were taken in this study, but they showed enhancement in heat transfer and a fourfold increase in nucleation sites – indicating at least some nanoparticles deposited on the surface. Wen and Ding [35] used gamma phase Al_2O_3 nanofluid boiled on a stainless steel disc of micron-sized surface roughness. The authors found no particle deposition during their experiments. Wen and Ding [36], in another study with a similar set-up except with titania (TiO_2) nanoparticles, showed an even larger enhancement (~50%) in boiling heat transfer. The authors, again, did not see much particle deposition. Truong [41] found very high enhancements (up to 68%) in heat transfer during pool boiling experiments with silica (SiO_2) and Al_2O_3 water-based nanofluids. The author did a considerable amount of work to determine the amount and rate of particle deposition, indicating that it had a major influence on the enhancement [41]. Ahn et al. [45] boiled refrigerants on nano-structured surfaces in an effort to test critical heat flux enhancement. However, they saw 19–33% enhancement in nucleate boiling. The surfaces were formed using chemical vapor deposition of multiwalled carbon nanotubes. This can be considered an extended case of nanoparticle deposition – the authors called it ‘nano-fin enhancement’ [45]. Coursey and Kim [47] found that Al_2O_3/H_2O nanofluids were unchanged in the nucleate regime, but Al_2O_3/Ethanol showed a significant improvement of 5–50% (depending on concentration) when boiled on a polished copper heater. The contact angle of the heater surface was significantly reduced after boiling in nanofluids.

In summary, these studies of dilute nanofluids showed enhancement ranging from 15–68% in nucleate boiling heat transfer. The studies used a wide variety of materials and geometries for nanoparticles and heaters. Most of them noticed a deposition of nanoparticles on the heater surface after boiling.

2.2. Literature showing degradation

The literature which concluded nanofluids were detrimental to pool boiling heat transfer performance showed a decrease in heat transfer ranging from 10–40%. Bang and Chang [19] studied Al_2O_3 nanofluids on a surface with a roughness of a ‘few tens of nanometers’ which was controlled by sandpaper. Relatively high concentrations, up to 4% by volume, showed ~40% less heat transfer. The authors noted that the nanofluids significantly changed the surface roughness especially after the heated surface was taken to critical heat flux. Das et al. [21], the pioneers in this area, boiled Al_2O_3 nanofluids on a standard and a roughened cartridge heater, $R_a = 0.4$–1.6 μm, respectively. In all tests the nanoparticles hindered heat transfer. Das et al. concluded that particles fouled the heated surface and caused deterioration. Jackson and Bryan [23] tested Au nanofluids on a Cu block at various pressures. Overall, Jackson found that heat transfer was reduced and the surface roughness was increased by the nanofluids. Kim et al. [24] tested several nanofluids (Al_2O_3, ZrO_2, SiO_2) on stainless steel wires and plates. The authors saw degradation, but since the electrical resistivity-temperature curve for stainless steel was not well known, it was mostly a qualitative result. The authors *did* find that a significant amount of particles was deposited on the heated surface (increasing surface roughness) and that the contact angle was reduced from ~80° to 8–36°, depending on conditions. Milanova and Kumar [29] also tested several types of nanofluids: Al_2O_3, SiO_2, and ceria (CeO_2). The authors looked at the effect of changing the pH in pool boiling experiments. The authors observed, in most cases, a decrease in nucleate boiling heat transfer. They also noted

Table 1
Review of experiments with nanofluid boiling.

Researcher(s)	Heater type	Nanofluid	Results	Particle deposition
Liu et al. [28]	Grooved Cu block	CuO/H_2O	Enhancement, 25–50%	Yes, a bonded coating
Shi et al. [32]	Cu block, $D = 60$ mm	Al_2O_3, Fe/H_2O	Enhancement, up to ~60%	Yes
Tu et al. [33]	Vapor deposited Ti heater, 26 × 40 mm	Al_2O_3/H_2O	Enhancement, up to ~64%, 1 data set	Yes
Wen et al. [35]	Stainless steel disc, $D = 150$ mm	γ-Al_2O_3/H_2O	Enhancement, up to ~40%	No
Wen et al. [36]	Stainless steel disc, $D = 150$ mm	TiO_2/H_2O	Enhancement, up to ~50%	No
Witharana [37]	Cu block $D = 100$ mm	Au, SiO_2/H_2O, EG	Enhancement, up to ~15–20%	Not studied
Truong [41]	Stainless steel wire	Al_2O_3, SiO_2/H_2O	Enhancement up to 68%	Yes, measured
Ahn et al. [45]	Nano-structured Cu block	*MWCNTs/PF-560**	Enhancement 19–33%	Yes, by design
Coursey and Kim [47]	Oxidized/metalized Cu block	Al_2O_3,/H_2O or ethanol	Enhancement 0–50%	Yes, extensive surface testing
Bang and Chang [19]	Rectangular, 4 mm × 100 mm	Al_2O_3/H_2O	Deterioration ~20%	Yes
Das et al. [21] (pioneer)	Smooth/rough, cartridge heaters	Al_2O_3/H_2O	Deterioration, 10–40%	Yes
Jackson and Bryan [23]	Cu Block	Au/H_2O	Deterioration, 10–25%	Yes
Kim et al. [24]	Stainless steel wire, $D = 0.38$ mm	Al_2O_3, ZrO_2, SiO_2/H_2O	Deterioration	Yes
Milanova et al. [29]	NiCr wire, $D = 0.32$ mm	Al_2O_3, SiO_2, CeO_2/H_2O	Deterioration	Yes
Zhou [39]	Horizontal Cu tube	Sub-cooled Cu/acetone	Deterioration	Not studied
Sajith [40]	NiCr wire, $D = 0.19$ mm	Al_2O_3, Cu/H_2O	Deterioration	Yes
Trisaksri, Wongwises [46]	Cylindrical Cu cartridge	TiO_2, Cu/HCFC 141b	Deterioration	Not studied
Chopkar et al. [20]	Cu block, $D = 60.5$ mm	ZrO_2/water	Little change	Yes, smoothened
Kim et al. [25]	Cu, var. orient., $T_{sat} = 60$ °C	Al_2O_3/H_2O	Little change	Yes
Narayan et al. [31]	Vertical tube heater, var. roughness	Al_2O_3/H_2O	−45% < Dep. on 'surface interaction parameter' <70%	Yes
Vassallo et al. [34]	NiCr wire, $D = 0.4$ mm	SiO_2/H_2O	Little change	Yes, thin coating
You et al. [38]	Cu, $T_{sat} = 60$ °C	Al_2O_3/H_2O	Little change	Not studied

* The fluid did not contain nanoparticles, but is mixed with the nano-structured surface.

that their nichrome (NiCr) wires were oxidized and that there was significant particle deposition during the boiling experiments. Zhou [39] conducted boiling experiments using Cu nanoparticles with acetone as the base fluid. A horizontal Cu tube was utilized as the heating surface and the effects of sub-cooling and acoustic cavitation were investigated. Zhou concluded that there was some enhancement for natural convection, but that the heat transfer during boiling was degraded. The author did not comment on particle deposition. Sajith et al. [40] used the hot wire method with Al_2O_3 and Cu/H_2O nanofluids. The authors attributed deteriorated boiling heat transfer to nanoparticle deposition. Trisaksri and Wongwises [46] showed deterioration under various pressures for TiO_2-R141b nanofluids on copper cartridge heaters. No information was presented about particle deposition.

For this group of papers, deterioration of 0–40% was seen – although many authors did not quantify the change as a percentage. Again, a wide variety of heater and particle materials was used. In most cases, particles were noticed to foul the heater surface due to boiling.

2.3. Literature showing both or little enhancement/deterioration

As mentioned above there were a few papers which could not be clearly placed in either the 'showed enhancement' or 'showed degradation' categories. These were papers that had both increased and decreased heat transfer during their tests or those that indicated little to no change. Chopkar et al. [20] conducted tests with zirconia (ZrO_2) based nanofluids on a Cu block. At low particle loading heat transfer was enhanced, but at higher concentrations or with repeated runs a decrease in heat transfer was seen. The authors noted that their heated surface became *smoother* after nanofluid boiling, as opposed to most studies that reported nanoparticle deposition on the heated surface. Tests were also carried out with the addition of surfactants. The authors concluded that, overall, it was too early to say whether heat transfer was enhanced or degraded. Kim et al. [25] conducted experiments with Al_2O_3 nanoparticles at low pressure. Their study investigated the effect of different heater orientations mostly with respect to critical heat flux. In this study bubble size was seen to increase while bubble frequency decreased. In spite of these changes, the authors concluded that nucleate boiling heat transfer was unchanged for nanofluids. Narayan et al. [31] tested Al_2O_3 nanofluids on a vertical tube with a variety of surface finishes. The roughness of the heaters used ranged from 48–524 nm. The authors defined a 'surface interaction parameter' which was simply the surface roughness (R_a) divided by the average particle diameter. The authors stated that when the parameter is near or less than unity, boiling heat transfer is deteriorated. When the parameter is greater than one, roughness is much larger than particle size and heat transfer is enhanced. The authors concluded that nucleation sites can be basically blocked if particles are roughly the same size as the nucleation sites – causing deterioration. Otherwise systems can be engineered for enhancement in boiling heat transfer. Vassallo et al. [34] did experiments with SiO_2 nanofluids on NiCr wires. The wires in this study showed a thin coating after boiling. Overall, the data fell on both sides of the curve for pure water, so no conclusions about enhancement or deterioration could be drawn. You et al. [38] conducted experiments with Al_2O_3 nanoparticles at low pressure. This study focused mostly on critical heat flux. As in Ref. [25], bubble departure was decreased but bubble size was increased giving little net change in the nucleate boiling regime.

This group of literature shows a wide range of results for diverse surface-particle material combinations. Most interestingly, Narayan et al. [31] suggests that enhancement or deterioration can be controlled by surface conditions. All but one [38] of these studies noticed particle deposition as a result of nanofluid boiling.

2.4. Representation of the existing data

The classic correlation developed by Rohsenow [42] is widely believed to accurately capture pool boiling phenomena for most conditions. It has been noted, however, by some in the above literature [35,36] that deviation from the correlation occurs when nanoparticles are added. The correlation can be represented in the following form [40]:

$$q'' = \mu_f h_{fg}\left[\frac{\sigma}{g\cdot\Delta\rho}\right]^{-\frac{1}{2}}\cdot\left(\frac{1}{C_{sf}}\right)^{\frac{1}{r}}\cdot \mathrm{Pr}^{-\frac{s}{r}}\cdot\left[\frac{c_{pl}(T_w - T_{sat})}{h_{fg}}\right]^{\frac{1}{r}} \tag{1}$$

where q'' is heat flux, μ_f, h_{fg} the fluid viscosity and the latent heat of vaporization, σ, g, $\Delta\rho$ the surface tension, acceleration of gravity, and change in density, C_{sf} a surface constant, Pr the Prandtl number and s, r are constants, and c_{pl}, T_w, and T_{sat} the liquid specific heat and temperatures at the wall and at saturation.

The constants in Eq. (1) can change for different fluid/surface combinations. For example, pure water on a relatively smooth surface (polished with $^{4}/_{0}$ emery paper) matches the following constants: $s = 1.7$, $r = 0.33$, and $C_{sf} = 0.0142$ [43]. Vachon et al. [43] examined a large amount of data and concluded that the best fits for different conditions vary significantly. For instance, holding the other factors constant, C_{sf} can change from 0.0065 to 0.0215 for water on a ground or milled surface, respectively [43]. Of course a better fit can be obtained by changing the other factors, but for simplicity's sake we will compare data from the literature to the Rohsenow correlation for water only with $s = 1.7$, $r = 0.33$, $\sigma = 0.06$ N/m, and C_{sf} in the range 0.0065–0.05. This may seem like a small range for C_{sf}, but inspection reveals that it is essentially raised to the 3rd power. Therefore, the change from 0.0065 to 0.018 actually multiplies the equation by a factor of ~22. That said, Fig. 1 shows various existing water-based nanofluid boiling data is easily bounded by Rohsenow's correlation by adjustment of C_{sf}.

The literature data in Fig. 1 (and subsequent figures) was collected by reading them off graphs from various articles. As such, the data shown here should be taken as a representation of the literature, not the exact results of the authors. Fig. 1 reveals that since Rohsenow's correlation can bound the nanofluid boiling data, it can also be used as a reasonable fit. Thus, intermediate values of C_{sf} should allow the correlation to match well with most experiments. Since particles are expected to deposit on (and modify) the heated surface throughout boiling, C_{sf} must logically change during the process as well. The only literature data set that cannot be represented by Rohsenow's correlation is Kim et al. [24] – whose data start at exceptionally high superheat values.

2.5. Physical Interpretation of C_{sf}

Many important phenomena are lumped into the parameter C_{sf}. For the solid heater surface, C_{sf} takes into account thermophysical properties such as thermal mass and conductivity [48]. In general, though, the most complicated part of determining C_{sf} is that the solid, liquid, and vapor all interact at the surface. In the case of a nanofluid, complexity is added since there are also nanoparticles present at the surface. Micro- and nano-scale cracks, pores, and pits in the surface and even defects in the nanoparticles can affect this interaction [49]. Surface roughness is certainly a good indicator of the heater geometry (and of C_{sf}), but it is hard to discern which measurement – average, extreme, spacing, or some combination – and which measurement method is most indicative. Wettability and adhesion are also tied to geometry [49]. Thus, there is no simple equation that can be written to describe C_{sf}. Even if C_{sf} could be empirically broken down and analyzed for each liquid-surface combination, it would lose simplicity and generality. Therefore, C_{sf} will have to be interpreted as a constant which accounts for all the complicated interactions that happen at the interface.

3. Preparation/characterization of nanofluids

In order to add to literature data, particularly at high heat fluxes, under sub-cooled conditions, and to further quantify the effect of nanoparticles on boiling incipience, nanofluids were prepared based on Al_2O_3 nanoparticles and water. Alumina was chosen because it is the most widely used in the literature and it is of low cost. Al_2O_3 nanoparticles with a reported nominal average diameter of 20 nm were purchased from NanoAmor. The nanofluids were prepared by mixing the powder particles directly with deionized water – *no surfactant was added*. The samples were then placed in an ultrasonic processor (Hielscher UP200S) for ~45 min. We investigated volume fractions of 1% or less, since much of the literature is in this range. In fact, as mentioned above, a few researchers noticed that at more than 1% particle loading, a decrease in enhancement is possible.

Dynamic light scattering (DLS) measurements using a Nicomp particle sizing machine indicate that particles always agglomerate. The average aggregate size is found to be relatively consistent at 150–160 nm with a standard deviation of about 70–75 nm. Thus, agglomeration is somewhat insensitive to particle concentration. DLS testing also revealed that 24 h later the samples heavily clumped into 10–15 μm aggregates, showing that these fluids are unstable. Further, if the sample was boiled and then sized 24 h la-

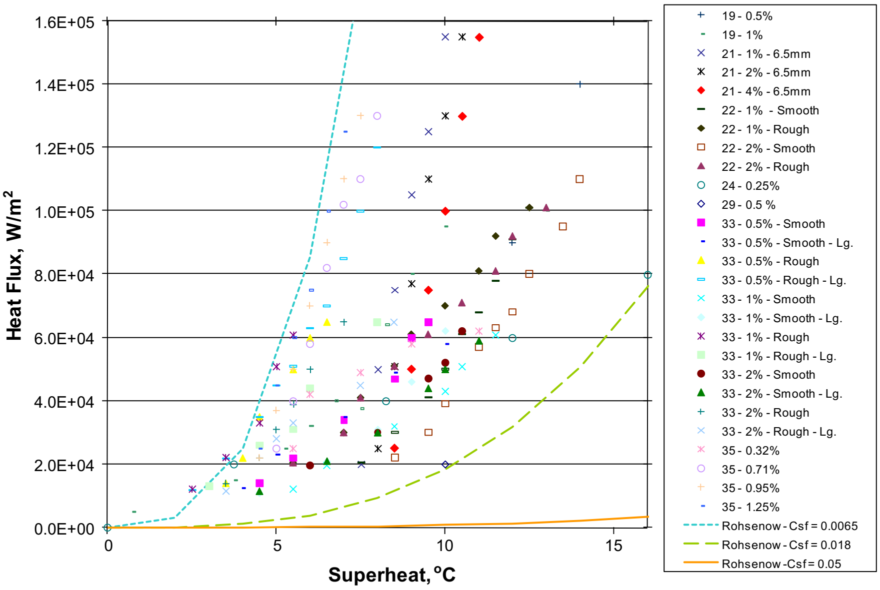

Fig. 1. Selected pool boiling data for water-based nanofluids (for a variety of nanoparitcle materials) as compared to Rohsenow's correlation [42] with different surface constants.

ter, the average particle diameter was found to be 18–28 μm. Thus, the rate of agglomeration seems to be influenced temperature as well as time. It should be noted that these results are given on a volume-weighted average, which yields particle sizes that lie between number and intensity-weighted averages.

4. Experiment

The hot wire method was used to conduct a simple pool boiling experiment. Fig. 2 shows a schematic of the boiling test cell. Current from a (BK Precision 1621A) DC power supply is passed through a known resistor (0.1 Ω ± 1% – from Mouser Electronics) and then through the heater wire (294R – donated by MWS Industries) back to the power supply. The voltage is measured over both of the resistors with a (Keithley 2001) multi-meter.

The heating wire is submerged in a 50 ml beaker containing the test nanofluid. The beaker is surrounded by an isothermal water bath (VWR 1209) which is held constant at ~100 °C. Unfortunately, due to heat transfer losses it was difficult to maintain 100 °C in the nanofluid at the beginning of testing. This was assumed to be acceptable since standard texts on pool boiling (such as Carey [44]) state that a small amount of sub-cooling should not influence the boiling curve significantly – especially at higher heat fluxes.

The wire is composed of 29% Ni, 17% Co, and 54% Fe. This wire was chosen because it had more than an order-of-magnitude higher temperature coefficient of resistance ($3.3 \times 10^{-3}\ \Omega/°\mathrm{C}$) as compared to conventional NiCr wire ($1.03 \times 10^{-4}\ \Omega/°\mathrm{C}$). The wire used in this study had a diameter of ~0.255 mm and a length of ~5 cm. A fresh wire was used for each test.

A standard thermometer (−20 to 150 °C range) is placed in the beaker to measure the bulk fluid temperature. The power supply is run under current-controlled conditions with discrete increases of 0.25 A every 2–3 min from 0 to 5 A (the upper limit of the power supply). This is done slowly in order to try to realize near steady-state conditions at each step. The voltage over our known resistor is measured to determine the current in the system. The wire temperature can then be back calculated using Eqs. (2)–(4):

$$\frac{V_{m1}}{R_{known}} = I_{PS} \tag{2}$$

$$\frac{V_{m2}}{I_{PS}} = R_w \tag{3}$$

$$\frac{R_w}{R_{ref}} = 1 + \alpha(T - T_{ref}) \tag{4}$$

where V_{m1}, R_{known}, and I_{PS} are voltage across the shunt resistor, shunt resistance, and current in the system, V_{m2} and R_w are voltage drop across the hot wire and wire resistance, and R_{ref}, T_{ref}, α, T are the reference resistance and temperature, thermal coefficient of resistance, and wire temperature, respectively.

In Eq. (4), α is the temperature coefficient of resistance mentioned above. In order to plot the boiling curve, the heat flux is also needed. This is found by the following equation:

$$q'' = \frac{I_{PS} V_{m2}}{\pi D l} \tag{5}$$

where q'', D, and l are the heat flux, wire diameter, and wire length, respectively. An error propagation analysis gives 2–3 °C error in the calculated temperature and 3–5% error in the calculated heat flux for this set-up. Sample uncertainties are shown in the following figures.

5. Experiment discussion

The experiments covered a wide range of phenomena: boiling incipience, nucleate boiling, sub-cooled boiling, and critical heat flux (CHF). CHF, however, is not presented due to limited data. Scanning electron microscopy (SEM)/X-ray dispersive scattering (XDS) analyses were performed – before and after heating – to investigate particle deposition.

5.1. Boiling Incipience

In pool boiling tests, the first point of interest is boiling incipience. This point marks the transition from the natural convection to the nucleate boiling regime. It can be noticed by a change in slope on a heat flux versus superheat curve. Fig. 3 shows the experimental results for nanofluids as compared to pure deionized water. A trend is indicated, in that boiling incipience occurs at lower superheat temperatures for the nanofluids compared to that for pure water. Furthermore, less superheat is required to initiate boiling with increasing nanoparticle volume fraction. This finding is presumably related to the deposition of nanoparticles on the heater surface, with the deposition density increasing with increasing nanoparticle volume fraction. An examination of the heater wire surface is described below.

5.2. Saturated nucleate boiling

The higher slope region to the right in Fig. 4 is referred to as the nucleate boiling regime. It is this part of the curve where researchers look for significant changes in the heat transfer rate since this is the operating range for many phase change applications. Our re-

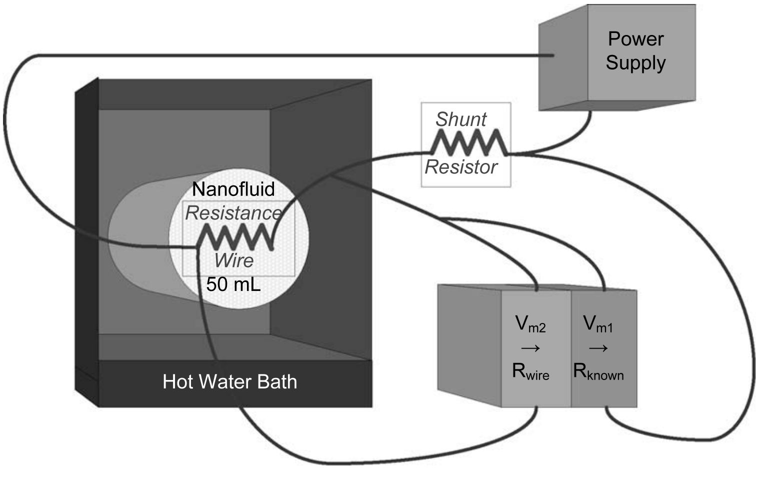

Fig. 2. Boiling cell diagram for the experiment – the test section is kept at saturated conditions using a hot water bath (VWR – Model 1209).

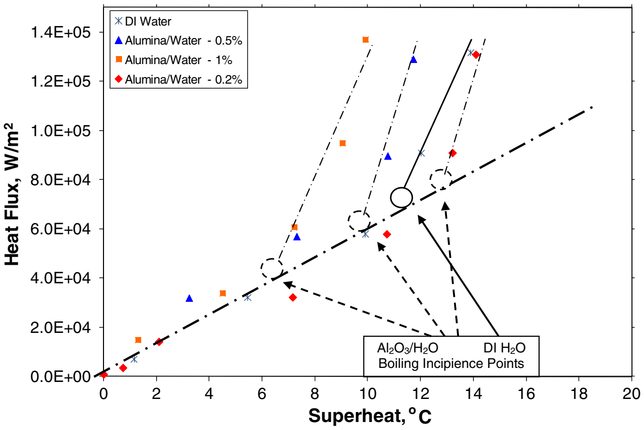

Fig. 3. Experimental results, from the current study, for Al_2O_3/H_2O nanofluids and DI water (circles and lines highlight changes in slope for these data).

sults show significant enhancement, 25–40% over that for pure water, for the higher nanoparticle loadings. Fig. 4 shows little enhancement for the 0.2% Al_2O_3 concentration, but a considerable shift to the left (i.e., enhancement) for the 0.5% and 1% concentrations. Thus, less of a temperature difference between the wire and the surrounding bulk fluid is necessary to dissipate the input heat flux for the higher concentrations.

Also, curves of Rohsenow's [42] model with variable C_{sf} are plotted against these data. As mentioned above, a changing C_{sf} is justifiable since nanoparticles interact with the heated surface increasingly during the test. Using this approach, the correlation fits most data points.

The bulk temperature of the test fluid starts at 95–99 °C. Thus, the first few data points in each test do not line up perfectly with Rohsenow's model. As noted above, according to conventional reasoning, a small amount of sub-cooling should have limited influence and will diminish at higher heat fluxes [44].

Fig. 5 presents the same data from this study, but also provides a direct comparison to the alumina nanofluid data found in the literature. It can be seen that the 0.5% and 1% data curves fall towards the left half of the literature data. This makes sense because only a portion of the literature demonstrated enhancement. Note that the present results, in general, extend to higher values of heat flux than do most of the existing data in the literature.

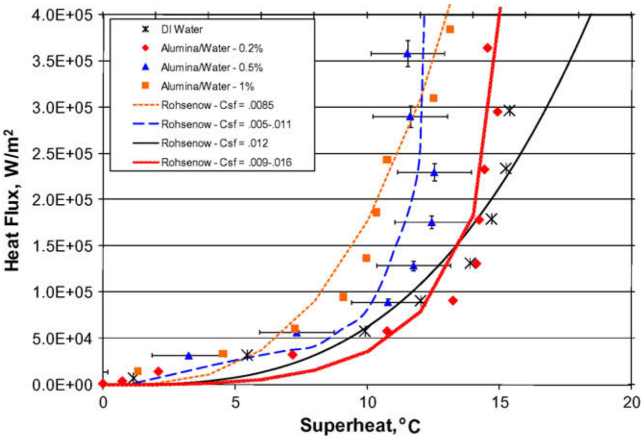

Fig. 4. Experimental results, from the current study, for Al_2O_3/H_2O nanofluids and Rohsenow's [42] model.

5.3. Sub-cooled boiling

Since the isothermal bath used in this study had difficulty reaching 100 °C, a few tests were conducted at lower bulk fluid temperatures – that is, sub-cooled pool boiling. Out of the surveyed pool boiling literature, only two articles examined the effect of sub-cooling on nanofluid boiling [27,39]. Li et al. [27] studied bubble interactions in sub-cooled nanofluid boiling and noticed that bubbles were more likely to cluster and/or overlap. Unfortunately, Li et al. did not generate boiling curves for comparison. Zhou et al. [39] concluded that the addition of nanoparticles does not change sub-cooled boiling. Zhou also used Cu/Acetone nanofluids which are not comparable to this work.

Fig. 6 shows boiling heat transfer is actually degraded during sub-cooled boiling of nanofluids, for this study. This was not expected since sub-cooling was assumed to have little impact on the boiling characteristics. A possible reason for this result is that when the fluid is sub-cooled, nanoparticles may be less likely to deposit on, and subsequently change, the boiling surface. This hypothesis is supported by the first few (slightly sub-cooled) data points in Fig. 4 which show that the nanofluids initially decrease heat transfer. Further, little particle deposition was seen in samples that were not taken above the boiling incipience point. Since bubbles are not seen until higher heat fluxes, sub-cooled boiling essentially extends the natural convection regime to higher heat fluxes.

One rationalization for degraded sub-cooled boiling in this study is that nanoparticle deposition may *only* occur during nucleate boiling. This could be explained by a high temperature gradient between the wire and the *liquid* fluid. Thermophoretic motion is expected to be important in nanofluids as it is dependent on the temperature gradient [50]. Thermophoresis would cause particles to migrate away from the high temperature wire.

5.4. Analysis of the heater wire surface

The last part of this study is dedicated to analyzing the wire surface. This is done by using a SEM fitted with XDS capabilities. Fig. 7 shows a heater wire after boiling in a nanofluid. Notice that the coating crumbles off when it is dry. This indicates most of the coating is weakly bound. The large chunks in Fig. 7 also illustrate that after boiling and drying the nanoparticles are highly agglomerated.

For surface analysis, the samples are lightly agitated in the nanofluid after boiling. This is done in order to remove the majority of the thick, loose coating. It is assumed that nanoparticles close to the surface would be most strongly bonded. The representative heater wires are then analyzed using the SEM/XDS machine. Fig. 8 shows a comparison of two wires after boiling – DI H_2O (A) and 0.5% Al_2O_3/H_2O nanofluid (B). In Fig. 8 (B) some nanoparticles can be observed on the surface. This is confirmed by an Al peak in the XDS results. In both boiling cases there is a large oxygen peak. This peak was not seen in a fresh wire, which indicates that boiling oxidizes the wire surface. Regrettably, due to the high iron (magnetic) content of the wire, clear SEM images were limited to a magnification of about 20,000×, or a 1–2 μm field of view. This is due to the fact that magnetic wires charge under high electron excitation, giving poor resolution.

SEM analysis also shows that surface defects (from extrusion) are approximately 1–2 μm wide. That is, the grooves running axially along the wire are approximately 10 times wider than the average particle diameter, or ~160 nm as measured by a dynamic light scattering system. This gives an estimated surface-interaction parameter as discussed in [31] of ~10. If the width of these grooves is roughly equivalent to their depth, then nanoparticle deposition would cause an increase in nucleation site density and lead to a more active boiling surface. In other words, nanoparticles smaller than the existing surface roughness could make the surface rough-

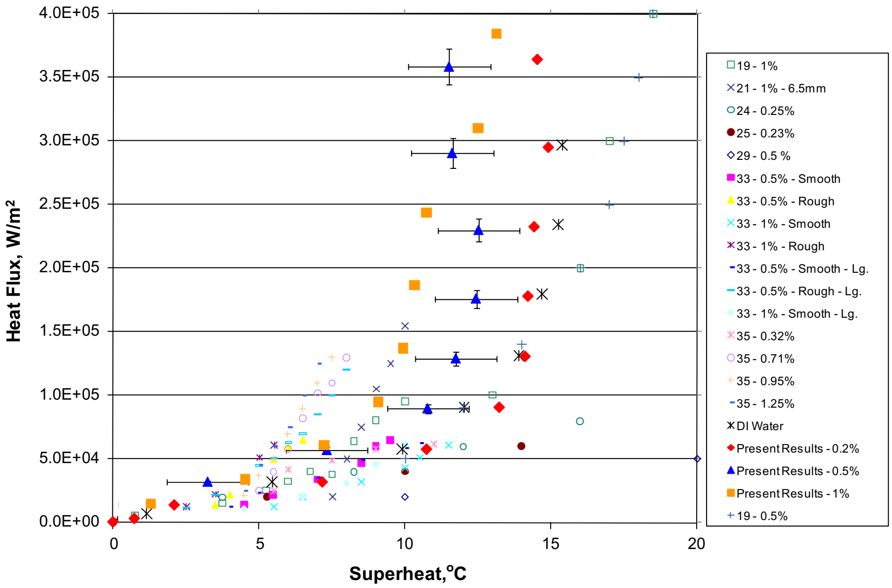

Fig. 5. Present nanofluid experimental results plotted against comparable alumina nanofluid pool boiling data from the literature – references indicated in the legend.

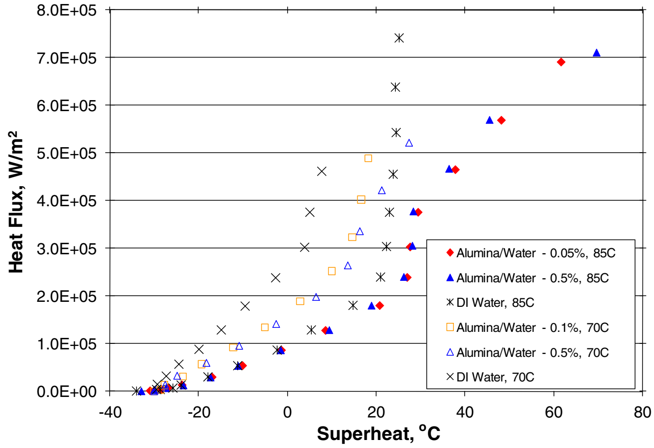

Fig. 6. Sub-cooled pool boiling tests from this study, for Al_2O_3/water nanofluids. The temperatures in the legend are the initial solution temperatures.

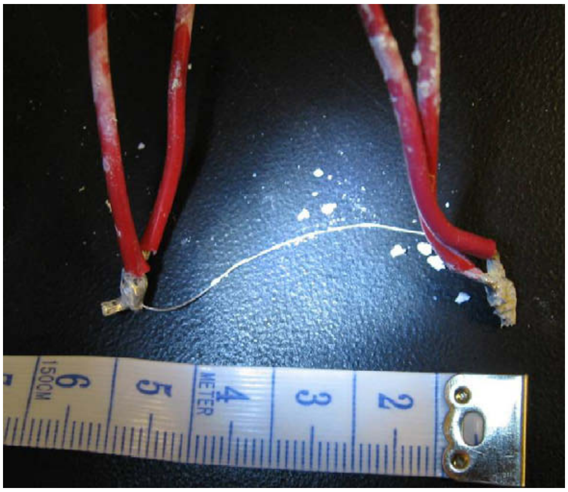

Fig. 7. A dry sample of heater wire (MWS294R – 17% Co, 29% Ni, 44% Fe) after boiling.

er – on the nanoscale – which would theoretically enhance nucleate boiling heat transfer. Many of the studies reviewed for this paper also suggest that nanofluids cause a significant change in surface roughness which can considerably shift the boiling [24,28,34,37]. Unfortunately, wires in this study were too small (with too high a curvature) to take direct surface roughness measurements.

6. Conclusions

The main findings in this paper are summarized as follows:

- Nanofluid pool boiling literature is in conflict over whether nanoparticles can enhance or degrade boiling heat transfer.
- Rohsenow's correlation [42] for pool boiling can be used to predict the performance of nanofluid boiling.
- Further, only C_{sf} (which depends on surface roughness and contact angle) needs to be changed to tailor Rohsenow's correlation to fit the experimental data. This indicates that nanoparticle surface deposition is the main factor involved in heat transfer perturbation.
- Our limited set of experimental data shows dilute (0.5–1% by volume) Al_2O_3 nanofluids initiate boiling (2–3 °C) earlier than pure water, and yield a heat transfer enhancement of 25–40% in nucleate boiling. Also, wires boiled in nanofluids showed particle deposition – which is thought to be the main reason for boiling enhancement.
- Boiling nanofluids under sub-cooled conditions led to a degradation of heat transfer, relative to saturated pool boiling of pure water.

The findings of this paper are in good agreement with other literature results which show enhancement using nanofluids in pool boiling. It also seems that changes in the surface play the most important role in determining whether enhancement is achieved. We hypothesize that surface deposition may be restricted during sub-cooled boiling due to the high temperature gradients – causing thermophoretic particle migration away from the wire. This effect may help explain the unexpected degradation during sub-cooled boiling. On the other hand, it *does* appear that nanofluidic systems can be engineered to operate at conditions which would achieve

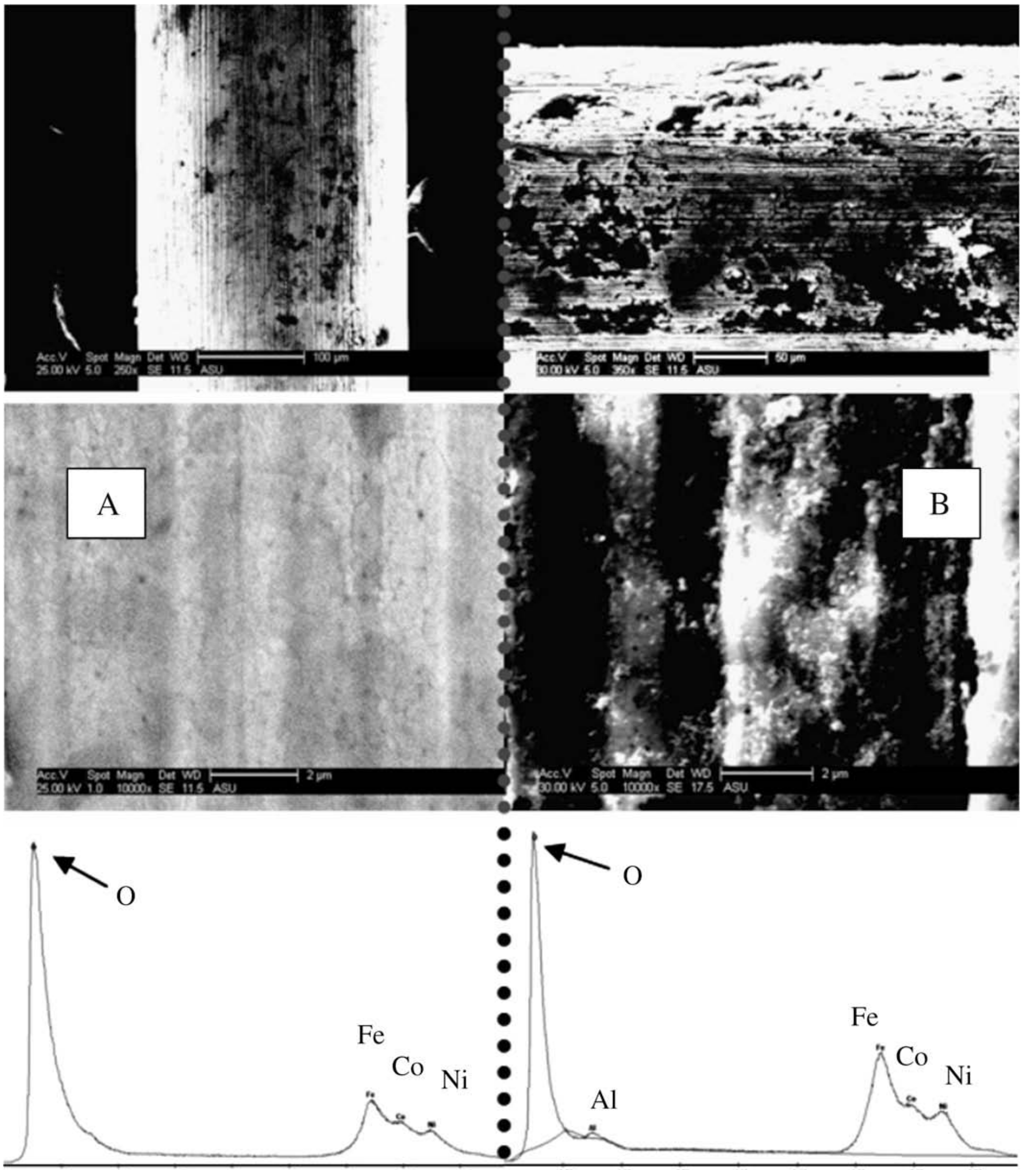

Fig. 8. SEM/XDS analysis of heater wires: (A) Boiled in H_2O (B) Boiled in 0.5%v Al_2O_3/H_2O nanofluid.

heat transfer enhancement during nucleate boiling. Considerable future work is needed, however, to define optimal/stable nanofluid heat transfer systems.

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