Boiling of Nanofluids at a Surface by Quantum Mechanics

T. V. Prevenslik
QED Radiations, Discovery Bay, Hong Kong, China
nanoqed@gmail.com

ABSTRACT: Boiling heat transfer (BHT) relies on liquid to vapor phase change in the continuous production of bubbles to dissipate heat from a surface. But as the heat flux to the surface is increased, the production of bubbles ceases and an insulating vapor film forms that causes the surface to overheat, the heat flux at which this occurs called the critical heat flux (CHF). Recently, nanofluids of water having less than 1% volume fractions of nanoparticles (NPs) have been shown to provide significant CHF enhancement over water alone, although the coefficient of BHT paradoxically is about the same. Classical heat transfer cannot explain this paradox, thereby prompting this quantum mechanics (QM) explanation. Atoms in NPs under BHT at temperatures as high as 1300K have thermal kT energy in the NIR and FIR, where k is Boltzmann's constant, T is absolute temperature, and NIR and FIR is near and far infrared. But NPs are submicron and by their size exclude NIR and FIR radiation, and therefore lack the heat capacity to conserve the absorption of heat by an increase in temperature. In BHT, the NPs conserve the kT energy in the NIR extracted upon colliding with the heated surface by QED induced frequency up-conversion to the EM confinement frequency of the NP that at UV levels leaks to the surrounding water. QED stands for quantum electrodynamics, EM for electromagnetic, and UV for ultraviolet. The CHF-BHT paradox is thereby explained by the NPs converting kT energy acquired from the heated surface to UV emission that is absorbed the surrounding water, thereby bypassing the boiling process allowing GHF enhancement without increasing the BHT coefficient. UV sensitive fluorescent water soluble markers are recommended as a means of verifying the correctness of QED induced heat transfer in BHT.

KEYWORDS: Critical heat flux, boiling heat transfer, nanoparticles, quantum mechanics

I. BACKGROUND

BHT may be defined as a heat transfer process where phase change from liquid to vapor occurs in bubbles. Since a very large amount of heat can be dissipated by BHT, the onset of CHF is of great interest because as bubbles cease portions of the surface are covered with an insulating film causing an excessive rise in surface temperature.

Numerous methods of enhancing the CHF have been cited in the literature. Roughening of the heated surface [1] with sandpaper and selecting microporous surfaces containing numerous bubble nucleation sites was found [2] to enhance BHT coefficients about 330% and increased CHF by about 100%. Surfactants were shown [3] to increase the BHT coefficient, although the CHF remained relatively unchanged. Millimeter or micron-sized particles [4] increased conductivity but was offset by sedimentation.

Since 1997, NPs are thought [5] to offer the most promise for enhancing CHF by increasing the thermal conductivity of the liquid. In 2003, alumina NPs in water were shown [4] to provide a 200% increase in CHF, although the BHT coefficients were paradoxically not increased above that of pure water. Indeed, the NP enhancement could not be explained with any existing CHF models. Specifically, the Zuber correlation [6] based on surface tension and heats of vaporization was unable to explain only a small fraction of the observed 200% increase in CHF suggesting that some unknown key factors missing in Zuber's correlation might exist.

Contrarily, the NP enhancement of liquid to vapor phase change was thought not related to the increased thermal conductivity [4] of nanofluids. Alumina NPs in water were tested [7] in 2005. The nanofluid was found to have a poor BHT coefficient compared to pure water, but the CHF was not only enhanced in horizontal but also in vertical pool boiling, by 32 and 13% respectively.

More recently, the issue of CHF and BHT of nanofluids was extensively discussed at the ASME Micro/Nanoscale Heat & Mass Transfer (MNHMT) Conference. In the area of light water nuclear reactors, alumina NPs in water [8] were thought to show promise in cooling by providing enhanced CHF. However, the paradoxical inability of nanofluids to increase the BHT coefficient remained unexplained consistent with prior [6,7] findings.

The paradox between CHF and BHT in pool boiling may be explained if NPs can be shown to provide a heat transfer mechanism that bypasses BHT and dissipates a significant amount of heat flux supplied to the surface. If so shown, the CHF may be enhanced while allowing the BHT to remain relatively unchanged.

But what is the NP heat transfer mechanism?

In 2008, the enhancement of thermal conductivity by NPs without boiling was shown [9] to be caused by

a mechanism called QED heat transfer. An updated version of QED heat transfer [10] was presented at MNHMT2009. By this theory, molecular collisions transfer thermal kT energy to the NPs in the FIR that cannot be conserved by an increase in temperature, and therefore conservation proceeds by the QED induced frequency up-conversion of FIR to UV radiation, the latter leaking to and penetrating the surrounding water.

In this way, NPs enhance heat transfer because the UV emission penetrates a greater distance in the a solvent than the FIR would without NPs. But the thermal conductivity of the nanofluid itself is not enhanced [9,10] above that given by long standing Hamilton and Crosser (HC) mixing rules [11].

In this paper, QED induced heat transfer is proposed as the mechanism that allows nanofluids in pool boiling to enhance CHF without increasing BHT. But not all particles produce EM radiation at UV levels. Micron and millimeter particles emit QED radiation in the FIR and microwave regions which is promptly absorbed at the particle surfaces, thereby explaining why the CHF in [4] was not enhanced.

.

II. PROBLEM STATEMENT

To provide a QM basis to the pool boiling phenomena in nanofluids based on QED induced heat transfer from NPs.

III. INTRODUCTION

The NPs in pool boiling of nanofluids emit both steady and transient EM radiation. Steady EM radiation is produced during molecular collisions by surrounding solvent molecules at 300 K while transient bursts of EM radiation occur upon the NPs contacting the heated surface up to 1300 K. .

A. Steady EM Emission
NPs emitting steady EM radiation upon molecular collision [9,10] are illustrated in Fig. 1
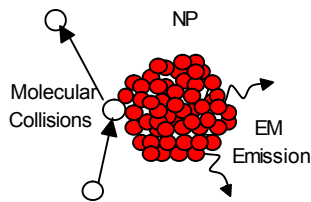

Fig. 1 Steady Pool Boiling Heat Transfer
NPs producing steady EM radiation from kT energy acquired by NPs upon collisions with water molecules.

Laser intensity aside, molecular collisions more efficiently transfer EM energy to NPs. Laser radiation of NPs scatters to reduce the Mie absorption [12]

efficiency. In contrast, collisions between NPs and the smaller surrounding molecules are inelastic so the full kT energy of the colliding molecules is transferred to NPs.

B. Transient Bursts of EM Radiation
Transient bursts of EM emission are produced from kT energy acquired as NPs contact the heated surface having temperatures as high as 1300K. The transient EM bursts are depicted in Fig. 2.
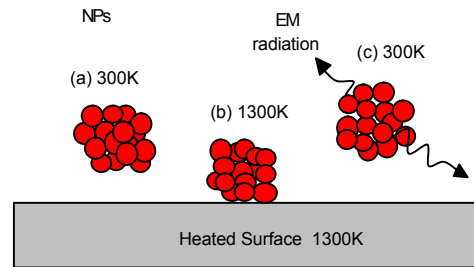

Fig. 2 Transient Pool Boiling Heat Transfer
NPs emitting a burst of EM radiation from kT energy acquired by NPs upon collisions with heated surface

NPs approaching (a), colliding (b), and leaving (c) the heated surface have kT energies at 300, 1300, and 300 K respectively. Molecular collisions emit steady EM radiation as shown in Fig. 1, but for clarity are not shown in Fig. 2. Upon collision with a heated surface, the NPs momentarily become a part of a macroscopic body (b) that by QM is allowed to have kT energy. Upon leaving the surface, the NP therefore has excess kT energy (c) that is not allowed by QM. Since the NP lacks specific heat to increase in temperature, the excess kT energy is induced by QED to be frequency up-converted and conserved by a burst of EM radiation.

IV. THEORY

In BHT of nanofluids, the NPs continually absorb thermal kT energy from colliding water molecules. At 300 and 1300 K, the kT energy of an atom resides in the FIR and NIR, respectively. Regardless, the NPs lacking specific heat cannot conserve the absorbed kT energy by an increase in temperature. Conservation may only proceed by the QED induced frequency up-conversion to the EM confinement frequency of the NP, typically in the UV that subsequently leaks to the surroundings. Since the UV is absorbed a distance from the NP, the CHF is enhanced, although the coefficient of BHT need not increase.

A. QM Restrictions
QM confines the EM wavelength λ of photons in NPs. At 300 and 1300K, the Einstein-Hopf relation [13] for the harmonic oscillator as a function of NP wavelength λ is shown in Fig. 3.
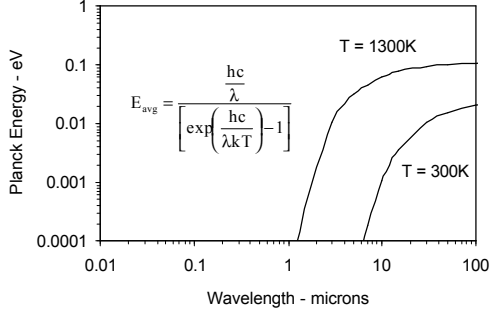
Fig. 3 Harmonic Oscillator at 300 and 1300 K
In the inset, h is Planck's constant, and c the speed of light.

At 300 and 1300 K, Fig. 3 shows atoms in NPs have full kT energy of 0.0258 and 0.11 eV for $\lambda > 50$ and 10 microns, respectively. Submicron NPs having wavelengths < 0.20 microns therefore exclude the available heat content of the atom at temperature. Hence, NPs do not have the heat capacity to conserve EM energy by an increase in temperature.

B. EM Confinement Frequencies

For NPs absorbing NIR and FIR radiation, the EM confinement is analogous [14] to the analogy of creating photons of wavelength λ by supplying EM energy to a QM box with walls separated by $\lambda/2$. For NPs of diameter D and refractive index n_r, the EM confinement frequency f and Planck energy E_P,

$$f = \frac{c}{\lambda}, \quad \lambda = 2n_r D, \quad \text{and} \quad E_P = hf \qquad (1)$$

C. Vanishing Specific Heat

Classical heat transfer conserves absorbed EM energy by an increase in temperature, but is not applicable to NPs because of QM restrictions on thermal kT energy. Both the Debye model of specific heat based on phonon vibrations of atoms in a lattice and Einstein's specific heat model of independent vibrations of the atoms as harmonic oscillators are only applicable [15] to steady heat transfer in macroscopic structures.

Instead, Planck's theory for photons in a cavity having a finite refractive index [16] is extended to non-thermal photons created by the QED induced frequency up-conversion of absorbed NIR and FIR radiation. The energy U of a spherical NP of diameter D with N photons,

$$U = NE_P = Nhf = \frac{hcN}{2n_r D} \qquad (2)$$

where, only the fundamental mode of EM confinement need be considered. For the specific heat C given by $\partial U/\partial T$,

$$C = 0 \qquad (3)$$

V. ANALYSIS

A. Steady EM Emission

The power Q_C transferred [17] to NPs in collisions with water molecules,

$$Q_C = \frac{\pi}{2\sqrt{3}} pPD^2 \sqrt{\frac{kT}{m}} \qquad (4)$$

where, p is the probability of full kT energy transfer, and P is the ambient pressure. The mass m of the water molecules is, MW/N_{avag} where MW is molecular weight and N_{avag} is Avagadro's number.

Absent an increase in NP temperature, the power Q_C is conserved by the QED induced emission of EM radiation,

$$E_P \frac{dN_P}{dt} = Q_C \qquad (5)$$

where, dN_P/dt is the rate of QED induced photons produced in the NP having Planck energy E_P. For alumina NPs having refractive index $n_r = 1.79$, the power Q_C with NP diameter D at temperatures of 300 and 1300 K is shown in Fig. 4.
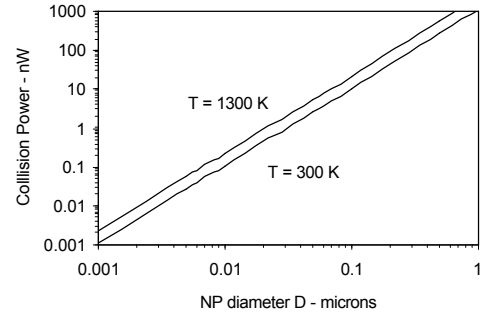

Fig. 4 Collisional Power Q_C and NP Diameter

The peak power Q_C for NPs < 0.1 microns is observed to be < 10 nW. The Planck energy E_P and rate of photons produced is illustrated in Fig. 5.
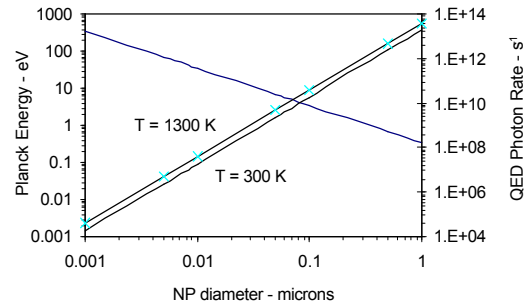

Fig. 5 QED Photon Radiation - Energy and Rate

In a nanofluid, the steady EM energy converted to heat Q_S upon absorption in the water depends on the total number N_{NPs} of NPs,

$$Q_S = N_{NPs}Q_C = V\phi Q_C \qquad (6)$$

where V is the volume and ϕ is the volume fraction of NPs in the nanofluid.

B. Transient Bursts of EM Emission

Upon the NPs contacting the heated surface, the NPs become part of a macroscopic structure that that by QM is allowed to have kT energy. For the surface at temperature T_H, the transient energy U_T of the NP,

$$U_T = \frac{\pi}{6}\left(\frac{D}{\Delta}\right)^3 3kT_H = \frac{\pi}{2}\left(\frac{D}{\Delta}\right)^3 kT_H \qquad (7)$$

where, Δ is the cubic spacing between NP atoms at solid density, $\Delta \sim 0.3$ nm. Lacking specific heat, the NPs leave the surface releasing the kT energy in a burst of EM radiation with power Q_T,

$$Q_T = \eta N_{NPs}U_T R \qquad (8)$$

where, η is the fraction of NPs that contact the heated surface and R is their rate of contact.

VI. DISCUSSION

The difficulty of comparing classical BHT theory with experiments [18] suggests a similar fate for QED heat transfer. Steady Q_S heat is not directly measured because it is included in the increase in thermal conductivity while the transient heat Q_T requires measurements of η and R.

The discussion of [4] to judge the correctness of QED induced heat transfer if nothing more serves as an example of what data should be measured in future experiments. A 10x10 mm^2 heater is placed at the bottom of a tank having cubical volume of about 2 liters, or 0.002 m^3. The sides of the tank are therefore about 12 cm. Transient heat Q_T is supplied to the heater to provide boiling. Strip heaters are placed on the tank sides maintain temperature, but do not contribute directly to boiling. The nanofluid consists of alumina NPs in water, although the size distribution of NPs is not reported. The analysis model is shown in Fig. 6.
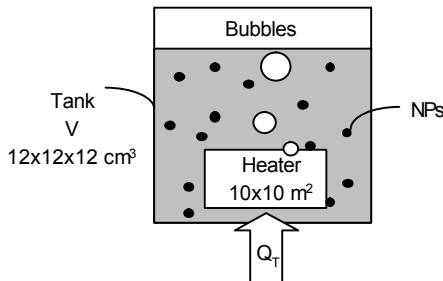

Fig. 6 Analysis Model

The CHF data (Fig. 2 of [4]) for pure water shows the heat flux q $\sim$ 500 kW/m^2 is enhanced to $\sim$ 1500 kW/m^2 for the nanofluid for a range of NP concentrations from 0.005 to 0.05 g/l. However, the data (Fig. 3 of [4]) shows the CHF saturates at $\sim$ 0.01 g/l. Hence, the NP concentrations at 0.01 g/l increase the CHF above that of pure water by $\sim$ 1000 kW/m^2 = 1x10^6 W/m^2. For a heater area A = 10x10 mm^2 = 1x10^{-4} m^2, the heat Q_T is therefore 100 W .

Taking the typical NP to have diameter D = 50 nm, the volume v = $\pi D^3/6$ = 6.54x10^{-23}m^3. For alumina at ρ = 961 Kg/m^3, w = 6.28x10^{-20} Kg. At 0.01 g/l = 0.01 Kg/m^3, the number density N of NPs is, N = 1.59x10^{17}/m^3. For the volume V = 2l = 0.002 m^3 of nanofluid in the tank, the number of NPs = NV = 3.17x10^{14}. Hence, the 50 nm NP volume faction ϕ = $N_{NPs}v/V \sim$ 3.17x10^{14} (6.54x10^{-23})/0.002 = 1x10^{-5}.

A. Steady Emission

Steady emission from increases the overall thermal conductivity of the nanofluid, but is not directly related to the increase in the CHF.

B. Transient Bursts

Transient bursts are directly related to bypassing the BHT at the heated surface. By this heat transfer mechanism, BHT is bypassed as collisions of NPs with the heater surface extract kT energy and then emit the EM radiation to the bulk nanofluid as they leave the surface. The process of collision with and leaving the heated surface may continue indefinitely, at least until the NPs coalesce with other NPs on the surface explaining why the CHF saturates at 0.01 g/l (Fig. 3 of [4]) .

Numerically, the thermal energy U_T at T_H = 1300 C removed per collision is, U_T = 1.38x10^{-13} J from Eqn. 7. For N_{NPs} = 3.17x10^{14}, Eqn. 8 gives Q_T = 43.74ηR. Given that Q_T= 100 W, ηR $\sim$ 2.28. The ηR relations for 50 and 100 nm NPs are plotted in Fig. 7.
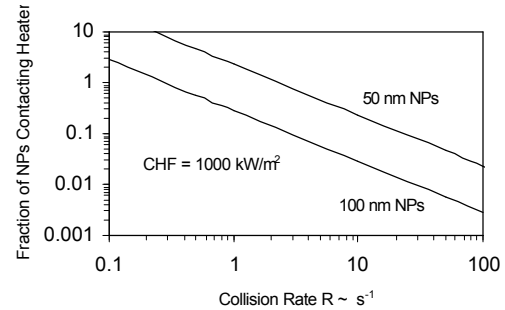

Fig. 7 Fraction η and Rate R for Q_T = 100 W

About a third of all 100 nm NPs are required to collide with the heater every second. However, it is unlikely that every second in a 12 cm cube of nanofluid that this fraction of particles will collide with the 10x10 mm^2 heater surface. The rate R and fraction η of NPs that collide with the heated surface are expected to be difficult to measure.

But the EM radiation from the NPs adjacent the heater surface prior to absorption may be possible using UV fluorescent dyes. The green fluorescent protein (GFP) is often used in genetics [19] as a marker. Many proteins, have significant light absorption bands in the UV that are of use and interest in biochemistry.

However, a UV fluorescent dyes may have absorption bands not accessible by the UV emission from the NPs, or the fluorescent emission my not be too low to be detectable. Small UV transparent windows may be required in nanofluid tanks to allow UV spectrophotometer measurements of NP emissions over a broadband range.

VII. CONCLUSIONS

• Nanofluids increase heat transfer, but any increase in thermal conductivity beyond that given by HC mixing rules is only apparent. NPs do not enhance the conductivity, but by QED heat transfer give the impression conductive has increased. NPs convert FIR radiation from collisions ro UV levels and beyond, the latter penetrating the nanofluid far more than the FIR would without NPs.

• In pool boiling, QED heat transfer occurs by both steady and transient processes. Steady heat transfer away from the heated surface is similar to that for nanofluids absent boiling. However, at the heated surfaces, the NPs provide transient heat transfer that bypasses the BHT. In a repetitive manner, the NPs collide with the heated surface extracting thermal kT energy. Upon leaving the surface, the kT energy is emitted as EM radiation at UV levels and beyond penetrates the bulk nanofluid and is absorbed away from the surface. In this way, the CHF is increased while the coefficient of BHT need not change.

• Verification of the correctness of QED heat transfer requires measurement of NPs as they collide and leave the heater surface. But this measurement in highly turbulent surroundings included bubble nucleation and growth may be next to impossible.

• The measurement of NP induced UV fluorescence from chemical markers in the nanofluid adjacent the heated surface may be possible, thereby explaining the increase CHF.

• Alternatively, the UV emission from NPs may be measured directly through suitable windows.

REFERENCES

[1] J.M. Ramilison, P. Sadasivan, and J. H. Lienhard, "Surface factors influencing Burnout on Flat Heaters," ASME J. Heat Transfer 114, 287, 1992.

[2] J.Y. Chang and S.M You, "Boiling heat transfer phenomena from microporous and porous surfaces in saturated FC-72," Int. J. Heat Mass Transfer, 40, 4437, 1997.

[3] G. Hetsroni, J.L. Zakin, and Z. Lin, "The effect of surfactants on bubble growth, wall thermal patterns, and heat transfer in pool boiling," Int. J. Heat Mass Transfer 44, 485, 2001.

[4] S.M. You, J.H. Kim, and K.H. Kim, "Effect of nanoparticles on critical heat flux of water in pool boiling heat transfer," Appl. Phys Lett., 83, 3374, 2003.

[5] S.U.S. Choi, Z.C. Zhang, W. Yu, F.E Lockwood, and E.A. Grulke, "Anomalous thermal conductivity in nanotube suspensions," Appl. Phys. Lett. 79, 2252, 2001.

[6] N. Zuber, "Hydrodynamic aspects of boiling heat transfer," AED Rep. AECU-4439, 1959.

[7] C. Bang and S.H. Chang, "Boiling heat transfer performance and phenomena of Al_2O_3 water nano-fluids from a surface in a pool," Int. J. Heat Mass Transfer, 48, 2407, 2005.

[8] J. Buongiorno and L.W Hu, "Nanofluid heat transfer enhancement for nuclear reactor applications," MNHMT2009-18062, Shanghai, December 18-21, 2009.

[9] T. Prevenslik, "Nanofluids by QED Induced Heat Transfer," IASME/WSEAS 6th Int. Conf. Heat Transfer, HTE-08, 20-22 August, Rhodes, 2008.

[10] T. Prevenslik, "Nanofluids by Quantum Mechanics," MNHMT2009-18014, Shanghai, December 18-21, 2009.

[11] R. L. Hamilton and O. K. Crosser, "Thermal Conductivity of Heterogeneous Two Component Systems," Ind. Eng. Chem. Fundam., 1, 187-191, 1962.

[12] C.F. Bohren and D.R. Huffman, *Absorption and Scattering of Light by Small Particles*, J. Wiley & Sons, 1983.

[13] R.W. Christy, and A. Pytte, *The Structure of Matter: Introduction to Modern Physics*, Benjamin, New York, 1965.

[14] T.V. Prevenslik, "Quantum Dots by QED," International Conference on Materials for Advanced Technologies (ICMAT), July 2-6, Singapore, 2007.

[15] C. Kittel, *Introduction to Solid State Physics*, New York, 2005

[16] R. Siegal and J.R. Howell, *Thermal Radiation Heat Transfer*, Taylor & Francis, New York, 2002.

[17] K.K. Das, Y.V. Rostovtsev, K. Lehmann, and M.O. Scully, "Thermodynamic and noise considerations for the detection of microscopic particles in a gas by acoustic Raman spectroscopy," *Optics Comm.*, 246, 551-9, 2005.

[18] J. Buongiorno, "Convective Transport in Nanofluid," ASME J. Heat Transfer, 128, 240, 2006.

[19] R. Tsien, "The green fluorescent protein" Annu Rev Biochem, 67, 509–44, 1998.