

Nanofluids by QED Induced Heat Transfer

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Abstract: - Nanofluids comprising nanoparticle (NP) suspensions in common solvents are generally thought to significantly enhance thermal conductivity. The transient hot wire method (THWM) test is used to infer thermal conductivity from the temperature response of a thermocouple (TC) a short distance away from an electrically heated wire (HW). Generally, the THWM tests show enhancements in conductivity far greater than given by long-standing Hamilton and Crosser (HC) mixing rules. The HC rules for thermal conductivity were derived by extending Maxwell's treatment of electrical conductivity for macroscopic particles (MPs) in a continuous solid state dielectric. However, the HC mixing rules have been routinely used to determine the effective thermal conductivity of nanofluids. This paper suggests a new approach to assess nanofluids based on quantum electrodynamics (QED) - that any enhancement found in THWM tests from HC mixing rules be treated as QED induced heat transfer, and not by enhanced conductivity itself. QED induced heat transfer restricts the kT energy of the NP atoms to vanishing small levels; whereas, the unconfined solvent molecules that collide with the NPs have full kT energy. Even though both NPs and solvent molecules are at the same temperature, collisions transfer kT energy to the NPs. QED requires the NP to not have kT energy, and therefore the kT energy transferred is conserved by the emission of electromagnetic (EM) radiation at the NP confinement frequency, typically beyond the vacuum ultraviolet (VUV). EM radiation is heat that at VUV frequencies significantly penetrates most solvents, thereby enhancing conductive heat transfer, even though conductivity itself is not increased and given by HC rules. QED induced EM heat transfer is extended to explain the enhanced chemiluminescence (CL) by EM emission from NPs in optically active luminol.

Key-Words: - nanofluids, nanoparticles, QED, mixing rules, collisions

1 Introduction

Historically, Maxwell first presented [1] the theory for the effective electrical conductivity of composite dielectrics that in principle may be extended to thermal conductivity of nanofluids. Excluding quantum effects, Hamilton and Crosser (HC) extended Maxwell's rules to thermal conductivity [2] for solid microparticles (MPs) of aluminum and balsa wood in a continuous solid phase of rubber. The HC mixing rules for MPs give the effective thermal conductivity k_{eff} by,

$$\frac{k_{\text{eff}}}{k_f} = \left(\frac{k_p + 2k_f - 2\phi(k_f - k_p)}{k_p + 2k_f + \phi(k_f - k_p)} \right) \quad (1)$$

where, k_p and k_f are the conductivities of the MP and solvent, and ϕ is the volume fraction of MPs.

Although NPs were not included in the HC verification, the HC rules have been routinely applied [3-7] to NPs in solvents over the past decade in comparisons with experimental results from the THWM. Kim et al. [3] showed enhanced conductivity of nanofluids depends only on NP size while emphasizing the fact that particle size is not

even a parameter in the HC mixing rules. Prompted by disparity with HC mixing rules, Jang's model [4] that relied on the Brownian motion of NPs was shown in [3] to be an unlikely explanation for NPs less than 10 nm. Jwo et al. [5] found homemade and commercial THWM devices to enhance conductivity by about the same amount.

Conversely, Zhang et al. [6] using the THWM found no enhancement of conductivity of nanofluids consistent with HC rules. Recently, Eapen et al. [7] found agreement with Maxwell's mean-field theory.

2 Problem Formulation

To show the enhancement of thermal conductivity in nanofluids from HC mixing rules may be explained by QED induced heat transfer.

3 Theory

QED induced heat transfer for a NP immersed in a nanofluid conserving collisional heat Q_c from the kT energy of solvent molecule by the emission of EM radiation is shown in Fig. 1.

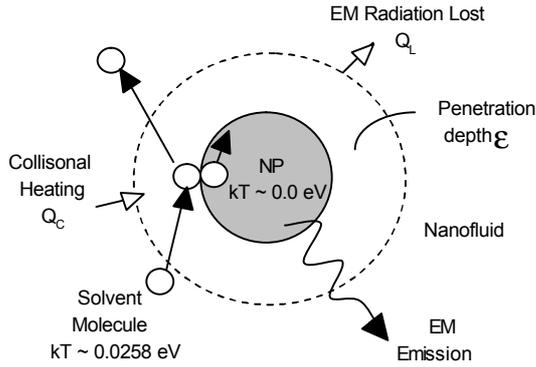


Fig. 1 – QED Induced Heat Transfer

NPs in nanofluids are similar to solid state quantum dots (QDs) under near infrared (NIR) laser irradiation. QDs produce visible (VIS) light by frequency up-conversion [8] of absorbed NIR photons by QED induced EM radiation. QED effects have been proposed [9] to show NPs in diesel engine exhaust under YAG laser irradiation emit EM radiation instead of increasing NP temperatures, the EM emission being the proper measure of NP concentration rather than cooling rate following heating to incandescence.

Unlike QDs, there are no NIR lasers in nanofluids to irradiate the NPs. But this is of no consequence because the NPs are maintained at ambient temperature by collisional heating from the solvent molecules. QDs and NPs find commonality in that both emit EM radiation at VUV levels without temperature increases.

3.1 EM Confinement Frequency

The NP atoms under EM confinement comprise frequency f and wavelength λ ,

$$f = \frac{c}{\lambda} \quad \text{and} \quad \lambda = 2Dn_r \quad (2)$$

where, c is the speed of light, D is the NP or MP diameter, and n_r is the refractive index. The Planck energy E_p of the QED photons induced in a NP is,

$$E_p = \frac{hc}{2Dn_r} \quad (3)$$

where, h is Planck's constant.

3.2 Thermal kT Energy and Gradient

The thermal kT energy of atoms in the NP or MP is given by the Einstein-Hopf relation [10] for the harmonic oscillator. At ambient temperature, the wavelength dispersion of average Planck energy E_{avg} shown in Fig. 2.

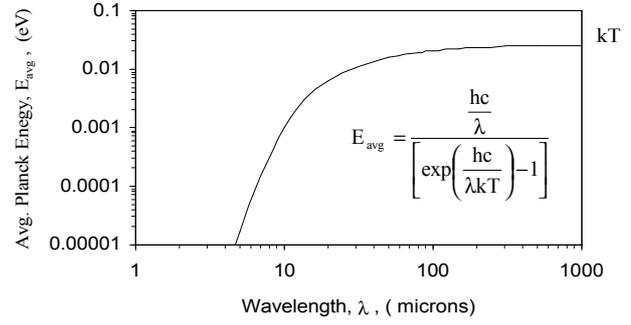


Fig. 2 – Planck Energy of Harmonic Oscillator at 300K. In the inset, k is Boltzmann's constant, and T is temperature

Classical heat transfer is applicable to bodies large in relation to the half-wavelength of FIR radiation at temperature. Fig. 2 shows the kT energy to saturate for $\lambda > 100$ microns, and therefore classical theory is applicable to MPs having diameters $D > \lambda/2 = 50$ microns.

Unlike MPs, QED forbids FIR radiation to exist in NPs because the NP diameters are smaller than the half wavelength of FIR radiation. Indeed, QED limits the lowest EM frequency that can exist in the NP to its EM confinement frequency. Typically, the EM confinement frequency for NPs is in the VUV.

In this regard, consider a NP having $D = 0.1$ microns with $n_r = 1$. Eqns. 2 and 3 give $\lambda = 2D = 0.2$ microns showing the NP atoms are under VUV confinement with Planck energy $E_p = 6.21$ eV. Fig. 2 shows the NP atoms have $kT \ll 1 \times 10^{-5}$ eV. In contrast, the solvent molecules in the unconfined EM state have full $kT = 0.0258$ eV energy equivalent to $\lambda > 100$ microns in Fig. 2.

Classical heat transfer requires a temperature difference for the transfer of heat. However, kT energy is EM and may be transferred from solvent molecules to the NP by collisions even though both are at the same temperature. This is may be understood from Fig 2 that shows the EM confined NP atoms having $kT \ll 1 \times 10^{-5}$ eV are at the same 300 K temperature as the EM unconfined solvent molecules having full $kT = 0.0258$ eV energy.

In this way, QED induces the solvent molecules having full kT energy to transfer their kT energy to the NPs. Since both NP atoms and solvent molecules are at the same temperature, the transferred kT energy does not increase the NP temperature. Instead, the kT energy in the NP now in excess of that allowed by QED at 300 K is conserved by EM emission.

3.3 QED Induced Collisional Heating

The QED induced heat flow into the NP may be expressed [11] in terms of the collision rate N_C of solvent molecules,

$$N_C = \pi D^2 \frac{P}{2mV_{rms}} \quad (4)$$

where, P is the ambient pressure, p is the probability of energy transfer, and m and V_{rms} are the mass and RMS velocity of solvent molecules. The velocity V_{rms} at ambient temperature T is, $V_{rms} = \sqrt{3kT/m}$.

The collisional heat Q_C transferred to the NP is,

$$Q_C = kpTN_C = \frac{\pi}{2\sqrt{3}} PpD^2 \sqrt{\frac{kT}{m}} \quad (5)$$

Hence, the EM emission from the NP necessary to conserve the absorbed collisional Q_C energy,

$$E_p \frac{dN_p}{dt} = Q_C \quad (6)$$

where, dN_p/dt is the rate of QED photons produced having Planck energy E_p at wavelength $\lambda = 2D$. For water molecules with $m \sim 3 \times 10^{-26}$ kg, pressure $P = 1 \times 10^5$ Pa, and energy transfer probabilities p of 0.001 and 1, the QED induced photon rate dN_p/dt and corresponding Planck energy E_p are shown in Fig. 3.

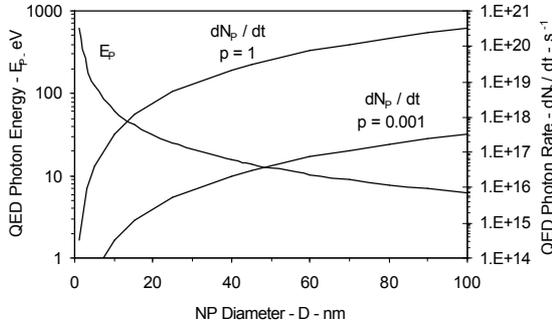


Fig. 3 – QED Photons and Rate induced in NP

3.4 Beer –Lambert Law - Penetration Depth

The Beer-Lambert law gives the depth ϵ by the absorption coefficient α of the solvent at the EM resonant wavelength $\lambda = 2D$ of the NP. The EM radiation intensity I at depth ϵ is related to the intensity I_0 at the NP surface by,

$$I/I_0 = \exp(-\alpha\epsilon) \quad (7)$$

For $\alpha\epsilon = 5.15$, 99% of the intensity I_0 is absorbed.

$$\epsilon = \frac{5.15}{\alpha} \quad (8)$$

The absorption α coefficient [12] for water solvent at ambient temperature is shown in Fig. 4.

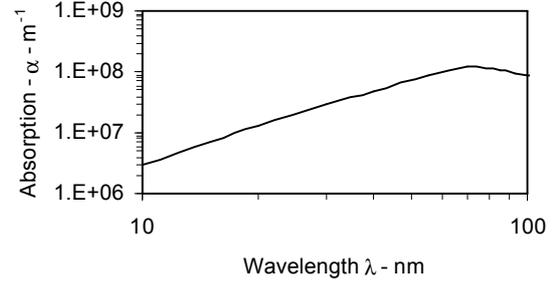


Fig. 4 – Absorption of Water at 300K.

3.5 QED Induced Volumetric Heating

The collisional heat Q_C absorbed by the NP is conserved by the emission of EM radiation that in turn is absorbed in the penetration depth ϵ of the solvent. The volumetric heat q generation is,

$$q = \frac{6}{\pi} \frac{Q_C}{((D+2\epsilon)^3 - D^3)} \quad (9)$$

The QED heating Q_C and volumetric heating q in the strong collision limit ($p = 1$) for NP diameters $D = \lambda/2 < 50$ nm are shown in Fig. 5.

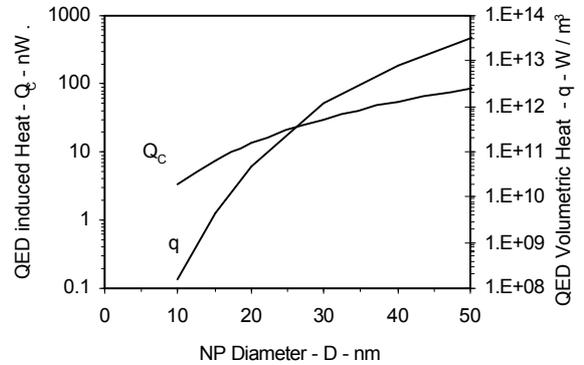


Fig. 5 – Collision Heat Q_C and Volumetric q Heating

3.6 Net NP Heating

The net Q_N heat produced by the NP is the difference between collisional Q_C gain and the EM emission Q_L loss.

$$Q_N = Q_C - Q_L = \eta Q_C \quad (10)$$

where, Q_N is a small fraction η of Q_C depending on the frequency of the emitted EM radiation. NPs emitting EM radiation that escapes the nanofluid have $\eta > 0$. In contrast, MPs emitting FIR and lower frequency EM radiation that is fully absorbed by the solvent have $\eta = 0$.

4 Analysis

The HC mixing rules do not include the net QED induced heat Q_N at each NP that must be supplied from the surroundings or a heater to maintain the temperature of the nanofluid. Consider a number N of NPs in a volume V of nanofluid swept out by an area A_S in an arbitrary direction S . The Fourier law for the effective conductivity k_S is,

$$Q + NQ_N = k_S A_S \frac{\partial T}{\partial S} \quad (11)$$

where, Q is the nominal heat flow and $\partial T/\partial S$ is the thermal gradient in the S direction. The number N of NPs is,

$$N = \frac{6}{\pi D^3} \phi V \quad (12)$$

where, ϕ is the volume fraction of NPs in the solvent.

$$\text{Taking } Q = k_{\text{eff}} A_S \frac{\partial T}{\partial S} \text{ gives}$$

$$k_S = k_{\text{eff}} + \frac{6\phi V}{\pi D^3} \frac{Q_N}{A_S \frac{\partial T}{\partial S}} \quad (13)$$

$$\text{Taking } \Psi = \frac{6V\eta}{\pi} \frac{Q_C}{Q} \text{ gives}$$

$$\frac{k_S}{k_f} = \left(\frac{k_p + 2k_f - 2\phi(k_f - k_p)}{k_p + 2k_f + \phi(k_f - k_p)} \right) \left(1 + \Psi \frac{\phi}{D^3} \right) \quad (14)$$

Consider a ZnO nanofluid [3] at volume fraction $\phi = 0.01$ of 10 nm NPs in water solvent. For ZnO and water, the conductivities are $k_p = 29$ and $k_f = 0.62$ W/m-K. Fig. 3 shows the NP induces Planck energy $E_p \sim 62$ eV at rate $dN_p/dt \sim 3.4 \times 10^8 \text{ s}^{-1}$. Fig. 5 gives $Q_C \sim 3.4$ nW and $q \sim 1.6 \times 10^8 \text{ W/m}^3$.

The THWM volume V is difficult to estimate. But [5] shows a 20 micron diameter wire about 15 mm long separated by about 10 mm from the thermocouple. Hence, $V \sim 3 \times 10^{-9} \text{ m}^3$. In [3], the THWM heat Q is about 0.138 W. Since the efficiency η that is a measure of heat Q_L loss is difficult to quantify, η is treated as a fitting parameter to the THWM test. For example, taking $\eta = 1 \times 10^{-8}$ gives $\Psi \phi / D^3 = 1411.6 \phi / D^3$, where D is in nm. By QED induced EM radiation, the HC thermal conductivity and THWM data are shown to qualitatively follow [3-7] as illustrated in Fig. 6.

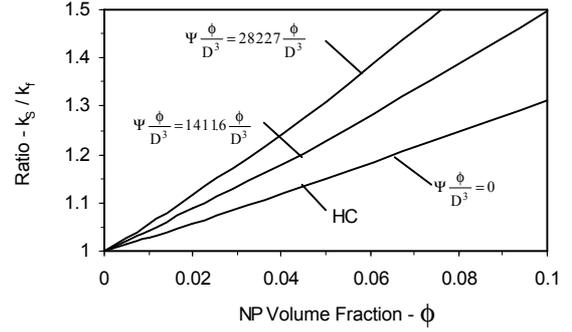


Fig. 6 – QED Effect on HC Thermal Conductivity

5 DISCUSSION

Over the past decade, nanofluids have been promoted as a way to improve heat transfer of coolants, and therefore the disparity between enhanced thermal conductivity found in THWM tests and the HC mixing rules is generally considered a problem because theory should agree with experiment.

However, the HC mixing rule based on classical physics giving effective conductivities less than that measured is not the problem. Thermal conductivity is a property that should follow classical physics of mixing. The problem is that NPs convert the temperature of the solvent into EM radiation that may escape to the surroundings, and therefore heat must be continually be supplied from the surroundings to maintain solvent temperatures. It is this supplied heat in the vicinity of the TC that confuses THWM tests that rely on the HW as the only source of heat.

Generally, NPs by having EM emission in the VUV spread the temperature of the NP over large penetration depths, thereby allowing heat to be loss to the surroundings. Conversely, MPs with EM emission frequencies in the FIR have virtually no penetration depth, and therefore do not lose heat to the surroundings. Heat supplied to balance lost EM emission is not necessary.

That any heat other than from the HW confuses the THWM tests was unequivocally demonstrated [3] by irradiating the nanofluid with a YAG laser. Certainly, HC mixing rules or Maxwell's mean-field theory would not be expected explain the laser enhanced thermal conductivity found in THWM tests.

But the YAG laser is an obvious source of NP heating; whereas, QED induced heating is subtle. Classical physics cannot explain why nanofluids show enhanced thermal conductivity. Indeed, the collisional heating of the NP atoms in a confined EM state by kT energy from the solvent in an unconfined EM state when both are at the same temperature may only be understood by QED.

6 CONCLUSIONS

QED induces the emission of high frequency EM radiation from NPs in solvents. Although most of the EM radiation is absorbed as heat, a small fraction escapes to the surroundings. To maintain nanofluid temperature, heat must be supplied that is not recognized in the THWM tests, and therefore the effective conductivity appears higher than that given by HC mixing rules based on HW heat alone.

The HC mixing rules give reasonably accurate estimates of effective thermal conductivity. Disparity with THWM tests may be explained with QED induced heating.

Classical heat transfer that conserves absorbed heat in a MP by an increase in temperature does not apply to NPs.

QED induced EM radiation suggests that nanofluids may improve the heat transfer of coolants by transferring heat over the penetration depths of EM emissions. Alternatively, the penetration depth makes the NP appear larger than its actual dimensions.

How the QED induced heat transfer enhances the effective thermal conductivity of nanofluids is illustrated by example, but experimental confirmation is required.

7 EXTENSIONS

In nanofluids, the NPs generate QED induced heating at VUV levels that effectively increases heat transfer. However, the nanofluids are not optically active, but if so, the same VUV radiation that produced heat in nanofluids may produce CL in optically active solvents.

Indeed, CL is enhanced [13] by simply adding gold NPs to luminol. To assure that the gold NPs were not oxidizing and producing CL by chemical reaction, UV-VIS absorption spectroscopy showed the oxidative state of the NPs did not change after CL emission. CL enhancement by NPs is yet another example of QED induced EM radiation [8,9].

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