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QED: The Fourth Mode of Heat Transfer?

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Abstract

Heat transfer proceeds by three modes: conduction, radiation, and convection. Conduction and radiation depend on the thermal properties of the material. Convection differs in that heat transfer depends on the properties of the fluid adjacent the material surface. However, heat transfer may also proceed by a fourth mode. Like convection altering the surface of the material, the fourth mode of heat transfer requires coating the surface of the material with a nanoscale layer of a material having a higher refractive index. Unlike conduction, radiation, and convection that find basis in classical physics, the fourth mode is based on QM with the heat transferred to the surroundings by EM radiation. QM stands for quantum mechanics and EM for electromagnetic. Classical physics that requires the atom to always have heat capacity does not predict any heat transfer enhancement for nanoscale coatings. But QM by requiring the heat capacity of the atom in nanoscale coatings to vanish precludes the conservation of EM energy by the usual increase in temperature. Instead, the heat into the coating under EM confinement is induced by QED to create non-thermal EM radiation that produces excitons (holon and electron pairs) that upon recombination ionize and charge the coating or emit the EM radiation to the surroundings. QED stands for quantum electrodynamics. Applications of QED heat transfer are briefly presented for thin films, nanoelectronics, and turbine blades.

Keywords: nanoscale heat transfer; quantum mechanics; quantum electrodynamics.

1. Introduction

Classically, heat transfer proceeds by conduction, convection, and radiation of which conduction is the most efficient. Conduction and radiation follow the laws of Fourier and Stefan-Boltzmann while convection transfers heat to a fluid by the Navier-Stokes equation. Finding origin in QM, QED heat transfer differs from classical physics by

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providing far more efficient cooling, but like convection requires surface modification by providing a coating having nanoscale thickness.

Enhanced heat transfer by providing nanoscale coatings does not seem intuitively correct. However, Hendricks et al. (2010) showed ZnO coatings having thicknesses of 50 -150 nm removed heat 4-10 X faster than by bare copper and aluminium surfaces, the porosity of ZnO thought to enhance heat transfer because of the increased area available. Recently, a review by Leal et al. (2013) of convective heat transfer between a solid and a fluid showed coating a surface with a porous metal increased the heat transfer area at the micron scale, but at the nanoscale little enhancement is expected. Regardless, porosity in nanoscale coatings is unlikely to provide 4-10 X the increased area necessary to account for the observed enhancement of heat transfer. Another mechanism is at play

2. Proposal

In classical physics, heat transfer in coatings does not depend on their thickness allowing conservation of EM energy to always proceed by temperature changes. QM differs by requiring the heat capacity of atoms under EM confinement at the nanoscale to vanish, and therefore the EM energy into the coating cannot be conserved by the usual change in temperature. But consistent with QM, Prevenslik (2010-2015) proposed EM energy conservation by QED instead of changes in temperature. At the nanoscale, EM energy absorbed is almost totally confined to the coating surfaces because of high surface to volume ratios. Atoms interposed between the coating surfaces therefore are placed under EM confinement that by QM require their heat capacity to vanish, i.e., Planck (1914). Under EM confinement, QED induces the absorbed energy to be conserved by EM waves standing between the surfaces as required by Feynman (1985). Excitons are created that upon recombination create QED induced EM radiation that ionizes and charges the atoms in the coating, or is emitted to the surroundings.

3. Theory

3.1. QM Restrictions

Classically, the atoms in nanoscale coatings always have the heat capacity to increase in temperature upon the absorption of EM energy irrespective of their thickness, i.e., there is no size effect in classical physics. QM differs in that the heat capacity of the atom depends on the thickness of the coating. A comparison of the thermal kT energy (or the heat capacity) of the atom by classical physics and QM by the Planck law is shown in Fig. 1

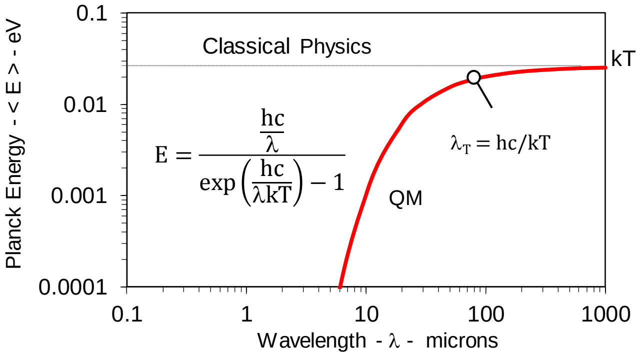

Fig. 1 Planck law of the Atom at 300 K
E is Planck energy, h is Planck's constant, c is speed of light,
k is Boltzmann's constant, T is temperature, and λ is wavelength

QM allows the atom in macroscopic coatings to have kT energy and increase in temperature for $\lambda > \lambda_T$. However, the kT energy decreases for atoms in coatings having $\lambda < \lambda_T$ and for nanoscale coatings with $\lambda < 100$ nm the atoms have virtually no heat capacity to conserve absorbed EM energy by an increase in temperature.

3.2 EM Confinement

QED as a mode of heat transfer depends on the high surface to volume ratios of nanostructures. A closely related mechanism is TIR standing for total internal reflection. In 1870, Tyndall showed light is trapped by TIR in the surface of a body if its RI is greater than that of the surroundings. RI stands for refractive index. However, TIR usually occurs in the surface of macroscopic bodies having low surface to volume ratios allowing absorbed EM energy to be absorbed throughout the volume of the body. EM confinement of nanostructures differs from TIR because the high surface to volume ratio requires almost all of the EM energy absorbed by the nanostructure to be spontaneously deposited in its surfaces.

Because of the high surface to volume ratio of nanocoatings, EM confinement occurs spontaneously in opposing coating surfaces upon the absorption of EM energy. For a coating thickness d, atoms interposed between the surfaces are placed under temporary EM confinement by the absorbed EM energy itself, i.e., there is no natural confinement of the atoms. QED induces the surface energy to create standing EM waves in the interposed coating thickness having half-wavelengths $\lambda/2 = d$. But the source of the standing wave is the EM energy in the confining surfaces, and since the EM confinement is no longer available, the standing wave is free to escape the coating. Hence, the QED induced standing wave behaves as if it were external EM radiation momentarily absorbed within the coating. Because of the nanoscale coating thickness d, the short wavelengths λ of QED induced EM radiation are in the UV and beyond having sufficient Planck energy to create excitons that ionize and charge the atoms, and if not the QED radiation is emitted to the surroundings. EM confinement is not permanent, sustaining itself only during absorption of EM energy, i.e., absent absorption there is no EM confinement and QED radiation is not produced.

QED relies on complex mathematics as described by Feynman (1985) although the underlying physics is simple to understand, i.e., EM radiation of wavelength λ is created by supplying EM energy to a QM box with sides separated by $\lambda/2$. In this way, QED conserves absorbed EM energy by frequency up-conversion to the EM resonance described by the thickness d of the coating. The Planck energy E of the QED radiation,

$$E = h\upsilon, \quad \upsilon = (c/n)/\lambda, \quad \lambda = 2d \tag{1}$$

where, n is the RI of the nanocoating.

4. Analysis

The wavelength of QED radiation depends on the RI and coating thickness. Typically, ZnO is used for electronics and YSZ for turbine blades. YSZ is yttrium-stabilized zirconia. QED radiation is shown in Fig. 2.

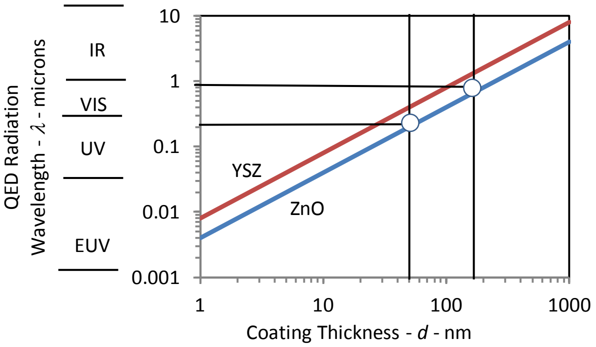

Fig. 2. QED Radiation Wavelength v. Coating Thickness

Generally, the QED radiation from 50 – 150 nm thick coatings having RI from 2 to 5 occurs from the UV to the NIR. In water, all wavelengths except for the VIS and near UV are absorbed almost immediately while air is transparent for all wavelengths except for trace atmospheric gases.

5. Discussion

5.1. Thin Films

Cooling by QED radiation in nanoscale coatings is not new, first studied by Kelemen (1976). Since then, thin film data has been misinterpreted for some time as reduced thermal conductivity because measured heat flow is lower than predicted by the Fourier equation. Because of this, the BTE was used by Liu et al. (2006) to explain the reduced conductivity in thin films by the scattering of phonons. BTE stands for the Boltzmann transport equation.

However, the BTE including the Fourier solutions are questionable because of incorrect heat balances assumed for the films. Prevenslik (2009) showed thin films emit QED radiation beyond the UV to the surroundings that is not included as a loss in the thin film heat balance, and therefore the thermal conductivity is concluded to be reduced from bulk. Alternatively, if the QED radiation loss is included in the balance, the conductivity remains at bulk. The exclusion of QED radiation from the heat balance is understandable as frequencies beyond the UV would normally not be observed during thin film experiments.

5.2. Nanoelectronics

QED radiation from nanoscale coatings shown by Prevenslik (2013, 2014a) to be perhaps the only way of cooling nanoelectronics, as natural convection from traditional cooling fins are difficult to implement at the nanoscale. Since QM requires the heat capacity of the atom to vanish, Joule heat from the electronics cannot increase the temperature of the coating. Instead, the Joule heat is emitted as QED induced EM radiation from the coating to the surroundings, thereby cooling the nanoelectronics.

Nanoelectronics coated by ALD offer a simple means of implementing QED cooling. ALD stands for atomic layer deposition. Of importance is nanoelectronics operate in clean room environments, and therefore air contaminants are unlikely to foul the coating and degrade the cooling provided by QED coating. In contrast, QED cooling by nanoscale coatings of heat exchanger tubes or turbine blades is more likely to be reduced because of fouling by contaminants in the surroundings.

5.3. Turbine Blades

Gas turbine blades are coated with TBC to insulate the blade from hot combustor gases. TBC stands for thermal boundary coating. See Lee (2006). In contrast, QED coatings Prevenslik (2014b) do not insulate the blade from high temperature, but rather cool the blade by converting combustor heat to non-thermal EM radiation that is dissipated in the surroundings. Under the TIR confinement in nanoscale TBCs, the heat capacity of the atom vanishes, and therefore the TBC cannot conserve heat from the combustor gases by the usual increase in temperature. Instead, conservation proceeds by the QED induced frequency up-conversion of combustor heat to non-thermal EM radiation at the EM confinement frequency of the TBC. QED cooling is passive avoiding the complexity of active fin and internal cooling by transferring the combustor heat away from the blades.

Turbine blade QED coatings differ from those in nanoelectronics because it is difficult, if not impossible to keep the coatings clean from fouling by combustor gas residues. Moreover, the application of nanoscale QED coatings of YSZ on nickel superalloys by APS and ALD is not yet demonstrated. APS stands for atmospheric plasma spray. Conventional APS processes based on 10–100 microns particles are unlikely to produce submicron TBCs. ALD of nanoscale YSZ coatings on Si_3N_4 are encouraging, but research to determine whether ALD is capable of producing submicron TBCs on nickel based superalloy turbine blades remains to be proven.

6. Conclusions

QED induced non-thermal EM radiation based on QM is proposed as the 4th mode of heat transfer alongside classical modes of conduction, radiation, and convection.

At the macroscale, conduction is thought to be the most efficient mode of heat transfer at ambient temperature with thermal radiation becoming important at elevated temperatures and convection relatively negligible. But at the nanoscale, the lack of heat capacity precludes the temperature `changes necessary for thermal conduction. What this means is conduction does not exist at the nanoscale and the Fourier equation is no longer applicable.

Applications of QED heat transfer for thin films, nanoelectronics, and turbine blades suggest that environmental fouling may limit the efficiency of nanocoatings for turbine blades. But thin films and nanoelectronics in clean environments should greatly enhance heat removal.

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