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QED COOLING OF GAS TURBINE BLADES

Thomas Prevenslik
QED Radiations
Discovery Bay, Hong Kong, China

ABSTRACT

Recent advances in cooling electronics by applying nanoscale coatings to circuit elements suggest gas turbine blades may be similarly cooled. Unlike TBC that insulate the blade from high temperature, QED cools the blade by converting combustor heat to non-thermal EM radiation that is dissipated in the surroundings. TBC stands for thermal barrier coating, QED for quantum electrodynamics and EM for electromagnetic. QED cooling finds basis in Planck's QM given by the Einstein-Hopf relation for the atom as a harmonic oscillator in terms of temperature and EM confinement. QM stands for quantum mechanics and TIR for total internal reflection. 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 TIR confinement frequency of the TBC. The only TIR requirement is the RI of the TBC is greater than that of the blade material. RI stands for refractive index. TIR confinement is the natural consequence of the high surface to volume ratio of nanoscale TBCs that concentrate the combustor heat almost entirely in the TBC surface. TIR confinement is not permanent, sustaining itself only during the absorption of combustor heat. In this way, the blade is cooled as the TBC converts the combustor heat into QED induced EM radiation that is absorbed in the surroundings. QED cooling is passive avoiding the complexity of active fin and internal cooling by transferring the combustor heat away from the blades. QED cooling by nanoscale TBCs is not new, having been mistaken for some time in thin films as reductions in thermal conductivity, examples of which are presented from the literature. QED cooling of turbine blades by nanoscale TBCs is expected to be a hot topic at ASME Turbo 2014.

BACKGROUND

QED cooling differs from the insulative nature of TBCs in that combustor heat is removed by EM radiation and dissipated in the surroundings. QED cooling originated from pool-boiling research [1] that showed nanostructured 50-150 nm coatings of zinc oxide on copper or aluminum substrates enhanced heat transfer up to 10X over bare surfaces. Heat transfer was thought enhanced by the increased area from the porosity in the flower-like structure of zinc-oxide, the petals of which promoting bubble formation and active boiling sites.

However, the notion that porosity increases heat transfer finds basis in classical physics that the temperature of a coating does not depend on its thickness. But QM requires the heat capacity of the atom to vanish in nanoscale zinc oxide coatings, and therefore the heat into the coating cannot be conserved by an increase in temperature. Unlike classical physics, QM precludes temperature changes in nanoscale coatings to take advantage of the increased area provided by the porosity to explain the enhanced heat transfer.

What this means is the increased heat transfer found in pool-boiling has nothing to do with the porosity of the zinc oxide coating. Rather, the nanoscale zinc oxide coatings provided the TIR confinement for QED to convert the combustor heat to EM radiation that bypassed the inefficient boiling process to be directly absorbed in the coolant water.

QED cooling does not require pool-boiling or water coolant, and may be absorbed anywhere in the ambient surroundings, the latter notion of great interest in cooling electronics. Indeed, air cooling by coating conventional electronics circuit elements with nanoscale zinc oxide or other suitable materials is especially attractive [2] and perhaps the only possible way to cool submicron circuit elements in nanoelectronics.

INTRODUCTION

Advanced gas turbine technology [3, 4] may rely on improvements in thermal efficiency and power output from diverse and perhaps even low temperature sources [1, 2] of QED cooling such as electronics. To double the engine power in aircraft gas turbines, the combustor gas temperature should increase from 1700 to 2000 C. High-temperature nickel based superalloy blades with TBCs of at least 125 micron thick YSZ using highly sophisticated advanced cooling concepts are thought [4] required to ensure high-performance gas turbines. YSZ stands for yttria-stabilized zirconia.

QED cooling based on QM is consistent with turbine blades in that YSZ has a RI of 4.2-4.8 [5] that is greater than that of nickel based alloys. However, QM also requires the thickness of the TBC to be submicron while YSZ thicknesses typically vary from 200 to 1000 microns. For QED cooling to be realized in turbine blades, TBC thicknesses must be significantly reduced. Indeed, transpiration film cooling in combination with a porous ceramic TBC [6] was recently developed in a plasma spraying process had thickness of 500 – 5000 microns.

Whether submicron TBCs of YSZ can be applied by APS or ALD to nickel based superalloys is an important consideration to establish the feasibility of QED cooling of turbine blades. APS stands for atmospheric plasma spraying and ALD for atomic layer deposition.

PURPOSE

The purpose of this paper is to show how by applying nanoscale TBCs to gas turbine blades, the blade temperature may be significantly reduced as the heat from the combustor gases is emitted as EM radiation and absorbed in the ambient surroundings.

DESCRIPTION

QED cooling is illustrated for nanoscale TBCs applied to the conceptualized turbine blade in Fig. 1. The blade is taken to be a nickel based superalloy provided with submicron YSZ thick TBCs on all surfaces.

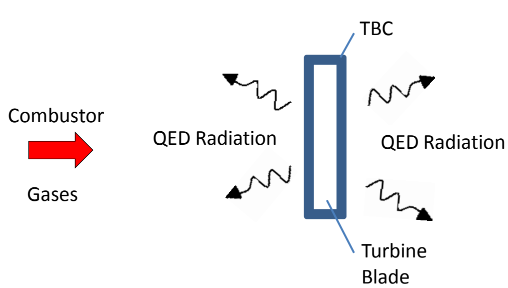

Fig. 1 QED Cooling
Turbine Blade and submicron TBCs

Hot combustor gases are shown to heat the front TBC surface in Fig. 1. For supramicron TBCs, the blade temperatures do indeed increase, but not for the submicron TBCs. Provided the RI of the TBC is greater than that of the nickel alloy blade, QM precludes the TBC atoms under TIR confinement to have the heat capacity to increase in temperature. Instead, conservation in the front TBC proceeds by the emission of QED radiation in the forward direction.

However, at least half of the combustor heat absorbed in the front TBC is emitted backward and absorbed by the blade causing its temperature to increase. But the back TBC temperature by QM also cannot increase, and therefore emits QED radiation backward into the surroundings. Actually, both TBCs emit QED radiation in the front and back directions, but as long as the surroundings can absorb the QED radiation without a significant increase in temperature, the blade temperature is not increased. In effect, QED converts the combustor heat to EM radiation that is absorbed in the surroundings without increasing the blade temperature.

THEORY

QM Restrictions

Classically, the atoms in submicron TBC have the heat capacity to increase in temperature upon the absorption of EM radiation irrespective of 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 TBC. A comparison of the thermal kT energy or the heat capacity of the atom by classical physics and QM by the Einstein-Hopf relation [7] for the harmonic oscillator is shown in Fig. 2.

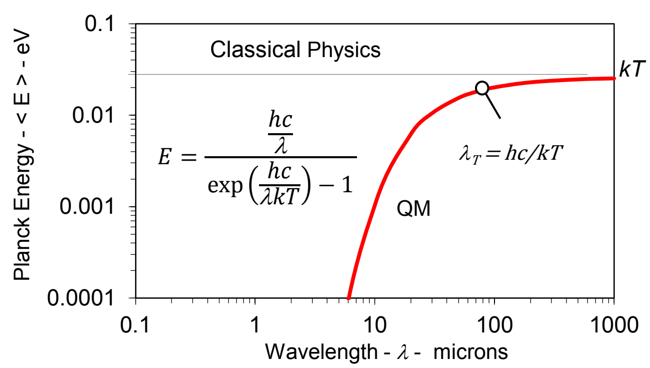

Fig. 2 Heat Capacity of the Atom at 300 K
is Planck energy, h Planck's constant, c speed of light,
k Boltzmann's constant, T temperature, and λ wavelength

QM allows the atom in supramicron TBCs to have kT energy for $\lambda > \lambda_T$ to increase in temperature. However, atoms in submicron TBCs confined to λ < 6 microns have kT < 1/250 eV while for λ < 100 nm the atom has virtually no heat capacity to conserve absorbed combustor heat by an increase in temperature.

TIR Confinement and QED Radiation

TIR has a long history. 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. Tyndall used water to show TIR confinement allowed light to be transmitted through curved tubes. TIR may confine any form of EM energy, although in gas turbine blades the confined EM energy is the heat from combustor gases dissipated in the TBCs.

TIR confinement requires combustor heat to be concentrated in the TBC surface that is a natural consequence of having high surface to volume ratios, i.e., combustor heat is almost entirely concentrated in the coating surface. Under TIR confinement, QED induces the absorbed heat to undergo spontaneous conversion to surface EM radiation, specifically QED induced radiation. However, TIR confinement is not permanent, sustaining itself only during the absorption of combustor heat, i.e., absent absorption there is no TIR confinement and QED radiation is not produced.

QED relies on complex mathematics as described by Feynman [8] although the underlying physics is simple, i.e., photons of wavelength λ are created by supplying EM energy to a QM box with sides separated by $\lambda/2$. In this way, QED conserves combustor heat by frequency up-conversion to the TIR resonance described by the thickness d of the TBC. The Planck energy E of the QED radiation,

$$E = h\upsilon, \;\; \upsilon = \frac{c/n}{\lambda}, \;\; \lambda = 2d \qquad (1)$$

where, n is the RI of the TBC.

ANALYSIS

The QED radiation emission wavelength induced from the conservation of combustor heat is depicted for TBC of YSZ on nickel based alloy substrates having lower RI in Fig. 3.

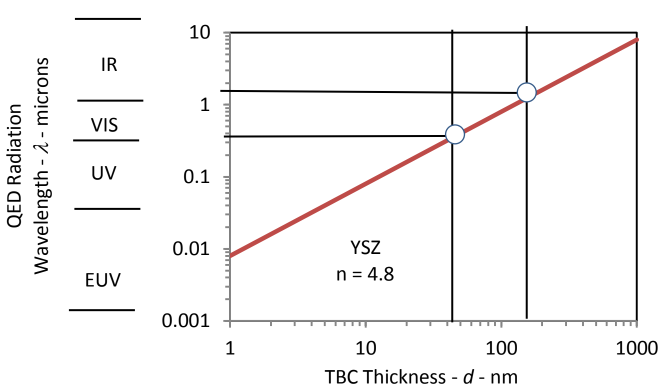

Fig. 3 QED Cooling
Wavelength of QED emission v. coating thickness

QED dissipates all combustor heat by emission of EM radiation to the surroundings. Depending on the thickness d of the TBC, QED emission may occur from the EUV to the IR.

Indeed, Fig. 3 shows for TBC having YSZ thicknesses of $50 < d < 150$ nm, the QED emission is in the VIS to the NIR. Air is transparent for all wavelengths except for trace atmospheric gases. Absorption of QED radiation in gas turbines therefore occurs at solid surfaces in the surroundings, and if macroscopic, the surface temperatures do indeed increase.

The QED radiation is successively emitted and absorbed by other turbine blades in the engine. Coating on the turbine casing allows the QED radiation to be finally dissipated to the ambient environment, although conventional cooling for the casing is likely more practical.

DISCUSSION

Thin Films

Cooling by QED radiation is not new, having been misinterpreted [9] for some time in thin films as reduced thermal conductivity because measured heat flow is lower than predicted by the Fourier equation. In this regard, the BTE simulating ballistic heat transfer by the scattering of phonons is thought [10, 11] to explain the reduced conductivity. BTE stands for the Boltzmann transport equation.

However, the BTE including the prior Fourier solutions are questionable because of the heat balances assumed for the films. The problem is thin films emit QED radiation beyond the UV to the surroundings [12] that is not included as a loss in the 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.

Paraphrasing the thin film experiments [10, 11] in terms of electronics cooling, the QED radiation actually cooled the films, but was interpreted as reductions in thermal conductivity. QED radiation dissipates absorbed heat to the surroundings, and therefore there is no need to reduce the conductivity to explain lower heat flows.

TBC by APS and ALD

Thermal spray processes usually involve the injection of a YSZ powder feedstock into a flame or a plasma jet. In the conventional APS process, the powder particles must have a diameter in the range of 10–100 microns making it difficult [13] to manufacture TBCs below about 10 microns in thickness.

ALD differs from APS by exposing the substrate surface to different vaporized precursors allowing ultrathin YSZ layers < 100 nm to be formed which are not possible with APS. Although data is not available for YSZ on nickel based superalloys, ALD of YSZ on Si_3N_4 showed [14] submicron thicknesses are feasible, but again research to determine whether ALD can manufacture submicron TBCs commercially on turbine blades remains to be proven.

CONCLUSIONS

The significant enhancement in pool-boiling heat transfer found by coating aluminum and copper with 50-150 nm zinc oxide is not caused by the porosity of the coating. QM precludes the coating from increasing in temperature to take advantage of the greater heat transfer provided by porosity. Instead, conservation proceeds by the creation of QED induced EM radiation under the TIR confinement of the nanoscale coating that upon emission is absorbed in the water coolant.

QED radiation is created independent of pool-boiling provided the coating is submicron and has a higher RI than the substrate. Hence, water coolant in coated substrates is not required, the consequence of which is the emission of QED radiation is simply dissipated in the ambient air surroundings, the latter of great interest because of its simplicity in cooling electronics. Indeed, air cooling by coating conventional electronics circuit elements with suitable nanoscale coatings is especially attractive and perhaps the only way to cool submicron circuit elements in nanoelectronics.

QED cooling is not new, but the beneficial effect has been misinterpreted as reduced thermal conductivity based on the BTE or the reduced heat flow from that predicted by the Fourier equation. By including QED radiation as a loss in the heat balance in nanotechnology, electronics circuit elements or otherwise, the beneficial effects of QED cooling may be fully realized.

With regard to QED cooling of gas turbine blades, enhancements similar to those in electronics may be expected to take advantage of QM, but may be difficult to implement in practice. Consistent with QM, TBCs of YSZ have RIs greater than nickel based superalloy blades, but the thicknesses varying from 200 to 5000 microns are far larger than the submicron thicknesses required by QM.

Research to determine whether submicron TBC thicknesses of YSZ on nickel based superalloys may be manufactured by APS or ALD is required to establish if the advantages of QED cooling offered by QM can be realized in practice for turbine blades.

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