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Minimum radiative heat transfer between two metallic half-spaces due to propagating waves

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ABSTRACT

The gap dependence of radiative energy transfer due to propagating waves between two identical metallic half-spaces separated by vacuum is investigated. The dielectric function of the metallic half-spaces is described by the Drude model. Analytical expressions for the minimum radiative heat transfer coefficient, h_{min}, and the gap, d_{min}, at which the minimum value of radiative transfer is attained are determined in terms of the parameters of the dielectric function and the absolute temperature T. We show that $h_{min} \propto T^2$ in the high temperature limit and $h_{min} \propto T^{7/2}$ in the low temperature limit.

1. Introduction

Radiative transfer between two closely spaced objects can exhibit features not captured by the classical theory of radiative transfer [1] because of near-field phenomena, such as the collective influence of interference and diffraction effects and the tunneling of evanescent waves. One of the most striking features is the enhancement of radiative transfer beyond the blackbody limit due to tunneling of surface phonon polaritons [2–5]. This enhancement has been observed experimentally by measuring radiative transfer between a microsphere and a planar substrate [6]. Though most of the recent studies on near-field enhancement have focused on the effect of surface phonon polaritons, what piqued the interest of researchers [7] in the mid-to-late 1960s was the enhancement of radiative transfer between metallic surfaces [7–11] at small gaps because of its importance in cryogenics. In this paper, we investigate the gap dependence of radiative transfer between two planar metallic surfaces. Unlike Polder and van Hove, who investigated this problem previously [11], our focus is not on the enhancement due to evanescent waves but rather on an initial decrease in radiative transfer as the gap decreases.[1] In contrast to enhancement due to tunneling of evanescent waves, which becomes apparent at sub-micron gaps (usually $\lesssim$500 nm), the minimum in radiative transfer occurs at larger gaps ($\approx 2\ \mu$m) [11]. Though evanescent waves contribute to radiative transfer at such gaps, as we will show, the decrease in radiative transfer can be explained by restricting ourselves to propagating waves. We realized in 2014, at NanoRad2014 (Second International Workshop on Nano-Micro Thermal Radiation) held in Shanghai, that Tsurimaki et al. [12] were also working on a similar problem. Tsurimaki et al. focus on the transition between the

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[1] We got interested in this problem, in part, after a discussion on this topic with Prof. Pinar Menguc.

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Nomenclature

ΔFF	relative change in h_{tot} relative to the far-field heat transfer coefficient h_{ff}
$\mathcal{T}_j$	polarization dependent transmissivity
c	speed of light in vacuum
d	thickness of vacuum gap between two half-spaces
d_{min}	vacuum gap at which h_{pw} attains a minimum
h_{ff}	far-field radiative heat transfer coefficient
h_{pw}	radiative heat transfer coefficient due to propagating waves
$h_{pw}^{(lg)}$	contribution to radiative heat transfer coefficient from modes active at larger gaps
$h_{pw}^{(sg)}$	contribution to radiative heat transfer coefficient from modes active at smaller gaps
$h_{tot}(d)$	total (propagating and evanescent) radiative heat transfer coefficient at vacuum gap d
k_0	ω/c, wavenumber in free space
k_B	Boltzmann's constant
k_{z0}	z-direction wavenumber in free space
k_{z1}	z-direction wavevector in half-space
n_1	real part of $\sqrt{\varepsilon_1}$
R_j	polarization dependent Fresnel reflection coefficient
R_j^a	approximation to R_j
T	temperature of half-spaces
x	k_{z0}/k_0, non-dimensional wavenumber
x_n	non-dimensional wavenumber for nth spike in $\mathcal{T}_j(x,y)$
z	non-dimensional frequency, ω/γ
ϵ_γ	non-dimensional damping frequency, $\hbar\gamma/(k_B T)$
ϵ_{ω_p}	non-dimensional plasma frequency, $\hbar\omega_p/(k_B T)$
γ	damping frequency in Drude model of $\epsilon(\omega)$
$\hbar$	Planck's constant divided by 2π
κ_1	imaginary part of $\sqrt{\varepsilon_1}$
λ	wavelength of electromagnetic wave in free space, $2\pi/k_0$
ω	angular frequency of electromagnetic wave
ω_p	plasma frequency in Drude model of $\varepsilon(\omega)$
σ	Stefan–Boltzmann constant
ε	dielectric function
ε_1	dielectric function of half-space
ε	inverse of non-dimensional gap, $\left[\frac{k_B T d}{\pi c \hbar}\right]^{-1}$
y	$\hbar\omega/(k_B T)$

far-field regime and the near-field regime between different types of materials (silicon carbide half-spaces and aluminum half-spaces). In this paper, we focus on radiative transfer between metallic half-spaces and the emphasis is on deriving analytical results.

The structure of the paper is as follows: In Section 2, we will describe briefly the theoretical basis for determining the radiative transfer between two identical half-spaces separated by a vacuum gap. In Section 3, we derive expressions for gap dependent radiative heat transfer coefficient due to propagating waves. Analytical expressions for radiative transfer at vacuum gaps beyond the value at which the minimum radiative transfer occurs are derived in Section 3.1; analytical expressions for vacuum gaps from contact to the minimum gap are derived in Section 3.2. In Section 4, analytical expressions for the minimum gap d_{min} and the minimum heat transfer coefficient h_{min} are obtained, from which the dependence of h_{min} on the temperature and other optical properties of the metals can be extracted. The influence of evanescent waves and the possibility of measuring the decrease in radiative transfer are discussed.

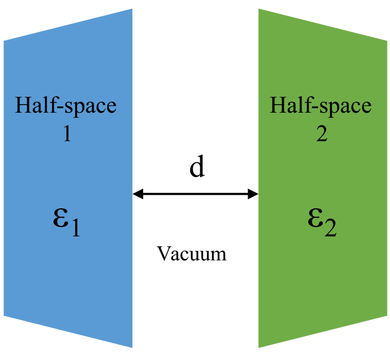

Fig. 1. Two planar, metallic half-spaces are separated by a vacuum gap d. It is assumed in our case that the two half-spaces are silver ($\varepsilon_1 = \varepsilon_2 = \varepsilon_{Ag}$).

2. Theoretical framework

Even though we focus only on propagating waves, classical theory of radiative transfer is insufficient to capture interference effects due to multiple reflections of plane waves. Hence, we use Rytov's theory of fluctuational electrodynamics [13,14] and the dyadic Green's function formalism to model heat flow between two half-spaces separated by a vacuum gap [15]. Since the theory of fluctuational electrodynamics has been discussed extensively in many publications [15,16], we use the well-known result for the linearized radiative heat transfer coefficient between two half-spaces of identical material separated by a vacuum gap of thickness d (see Fig. 1):

$$h_{pw}(d,T) = \frac{k_B^4 T^3}{4\pi^2 c^2 \hbar^3} \int_0^\infty dy \frac{y^4 e^y}{(e^y - 1)^2} \sum_{j=s,p} \int_0^1 dx x \mathcal{T}_j(x,y) \quad (1)$$

where $j = s,p$ refer to transverse electric and transverse magnetic polarizations, respectively, $y = \hbar\omega/k_B T$ is a non-dimensional frequency, ω is the angular frequency, k_B is Boltzmann's constant, $2\pi\hbar$ is Planck's constant, T is the temperature of the two objects, c is the speed of light in vacuum, $k_0 = \frac{\omega}{c}$, $x = \frac{k_{z0}}{k_0}$ is the non-dimensionalized z-wavevector in vacuum (k_{z0} is the dimensional wavevector), $\mathcal{T}_j$ is the *generalized transmissivity* and is related to the