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Transition from the incoherent to the coherent regime for propagative-wave based thermal radiation

Y Tsurimaki[1,2], P-O Chapuis[1], J Okajima[2], A Komiya[2], S Maruyama[2], R Vaillon[1]
1 Université de Lyon, CNRS, INSA-Lyon, UCBL, CETHIL, UMR5008, F-69621 Villeurbanne, France
2 Institute of Fluid Science, Tohoku University, 2-1-1, Katahira, Aoba-ku, Sendai, 980-8577, Japan

E-mail: rodolphe.vaillon@insa-lyon.fr

Abstract. The transition from the incoherent to the coherent regime for thermal radiation between bodies trough a transparent medium is discussed. The canonical case of two parallel semi-infinite planar media is used as a basis to provide an insight into the physics and quantities ruling the distance at which coherent effects have an impact on the propagative component of the net heat flux exchanged. A practical criterion is proposed to define the distance below which radiation intensity framework should not be used, but instead fluctuational electrodynamics.

1. Introduction

Planck already stated that his theory would be valid provided all dimensions should be large compared to the wavelength under consideration [1]. This means that if the distance between bodies exchanging thermal radiation, or if the sizes of the bodies themselves are comparable to the wavelength, another theory is required. Fluctuational electrodynamics highlighted by Rytov and colleagues [2] provides the tool to model electromagnetic thermal radiation at small scales. Much attention has been paid to the strong enhancement of the net heat flux beyond the blackbody configuration. It gave rise to the advent of near-field thermal radiation as a new branch of radiative heat transfer (see two recent reviews and references therein [3,4]). However, much less analyses on the regime where the coherent effects of thermal radiation play a role have been proposed. It must be emphasized that this transition regime between the far-field and near-field regimes was observed in some simulation results since the early work of Polder and Van Hove [5], especially when the variations of the flux between the bodies is analyzed as a function of their separation distance. It was understood only recently that the net heat flux could be reduced far below the far-field value [6-9], and almost suppressed in some cases.

In this article, an in-depth analysis of the physics and parameters ruling the propagative component of the net radiation heat flux between semi-infinite plane-parallel plates derived from fluctuational electrodynamics is proposed. In particular, the distance between bodies at which thermal radiation cannot be considered incoherent, i.e. modelled using the intensity, is determined. Its dependence on electromagnetic properties and temperatures of the plates is discussed.

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2. Theory, results and discussion

In the case of two semi-infinite plane-parallel bodies (media 1 and 3 on figure 1.a) separated by a vacuum gap (medium 2), the formulation of the total radiative net heat flux exchanged by the two bodies was given by Polder and Van Hove [5]. This flux is split into two components, one standing for the evanescent waves and the other for the propagative waves. They are solely function of the distance between the plates (d), temperatures (T_1 and T_3) and complex permittivities (ε_1 and ε_3) of the plates, assuming that materials are non-magnetic. A radiative heat transfer coefficient can be introduced as the temperature derivative of the flux and split into the evanescent and propagative components as well:

$$h^{\text{total}}(d,T) = \lim_{\Delta T\to 0}\frac{q}{\Delta T} = \lim_{\Delta T\to 0}\frac{q^{\text{prop}}}{\Delta T} + \lim_{\Delta T\to 0}\frac{q^{\text{evan}}}{\Delta T} = h^{\text{prop}} + h^{\text{evan}} \tag{1}$$

where superscript 'total' means that propagative and evanescent waves components are both taken into account. By doing so, radiative heat transfer can be analysed as a function of the product of temperature and distance $T.d$; this is more general than an analysis as a function of the distance only for several temperature differences between the plates.

When reflectivities of the bodies are large enough, i.e. for metals, and for a symmetric configuration, it was observed previously [6-9] that the total net heat flux can decrease below the far-field value when distance d is becoming smaller. The flux can reach a minimum and eventually rise up far beyond the blackbody limit because of the contribution of evanescent waves (figure 1.b). Distance $d_{\text{incoh-coh}}$ at which the far-field radiation incoherent regime does not hold anymore for propagative waves is under investigation in the following.

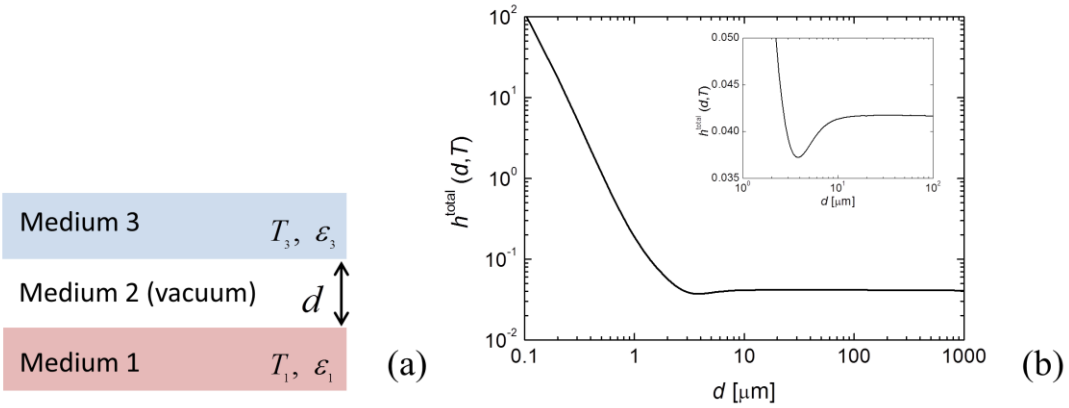


Figure 1. (a) Configuration under consideration. (b) Total radiative heat transfer coefficient as a function of distance between the plates for aluminum at 300 K.

A practical criterion is proposed to define the distance at which the transition from the far-field incoherent to the coherent regime for thermal radiation is taking place. It consists in stating that this is the distance $d_{incoh\text{-}coh}$ at which the flux has varied by 5%: $h^{\text{prop}}(d_{\text{incoh-coh}},T)/h^{\text{prop}}_{d\to\infty}(T) = 0.95$. On figure 2, this limit is plotted on a ($T.d$, T) diagram for several materials and temperatures. For comparison, the constant 2897.8 μmK from Wien's law is indicated. The wavelength where Planck's function is maximum ($\lambda_{\max}$), is also known to be close to the coherence length of a blackbody emitter [10]. When the plates are not black but grey (constant relative permittivity, here equal to ε_r = 100 + i 10^{-4}), the product $T.d_{\text{incoh-coh}}$ is found to be the same at any temperature, and is smaller than $\lambda_{\max}.T$. However, when real materials are considered, i.e. metals, the product $T.d_{\text{incoh-coh}}$ is much larger (around two to three times) and varies with materials and temperatures. These cases can be understood as being spectrally weighted sums, the weights being the spectral variations of permittivities and of Planck's

(Bose-Einstein) distribution function of modes. The analysis in terms of coherence length is not straightforward. The criterion of 5% variation does not necessarily coincide with any "physical" definition of what would be a coherence length of thermal radiation but it provides a limit which has a practical usefulness to state whether the far-field incoherent thermal radiation theory can be used or not for the propagating waves. This analysis will be completed by adding the cases of dissymmetric and dielectric materials. Finally, we underline that this transition length is also compared with the one associated to the transition from the propagative-wave to the evanescent-wave regime, that was not tackled here for the sake of brevity.

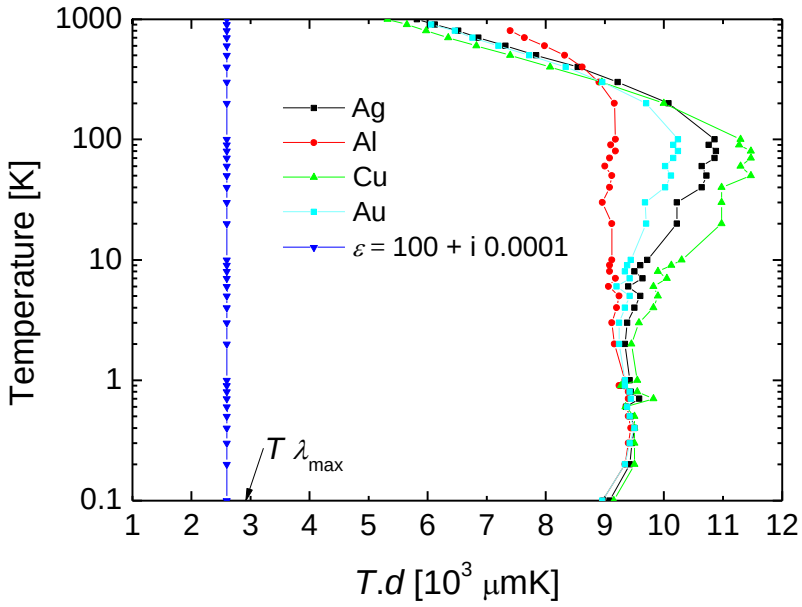


Figure 2. Plot on a (*T.d*, *T*) diagram of the limits $d_{\text{incoh-coh}}$ at which the transition from the far-field incoherent to coherent regime for thermal radiation takes place, for grey and metallic plates.

Acknowledgments
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