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Coherent regime and far-to-near-field transition for radiative heat transfer

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ABSTRACT

Radiative heat transfer between two semi-infinite parallel media is analyzed in the transition zone between the near-field and the classical macroscopic, i.e. incoherent far-field, regimes of thermal radiation, first for model gray materials and then for real metallic (Al) and dielectric (SiC) materials. The presence of a minimum in the flux-distance curve is observed for the propagative component of the radiative heat transfer coefficient, and in some cases for the total coefficient, i.e. the sum of the propagative and evanescent components. At best this reduction can reach 15% below the far-field limit in the case of aluminum. The far-to-near-field regime taking place for the distance range between the near-field and the classical macroscopic regime involves a coherent far-field regime. One of its limits can be practically defined by the distance at which the incoherent far-field regime breaks down. This separation distance below which the standard theory of incoherent thermal radiation cannot be applied anymore is found to be larger than the usual estimate based on Wien's law and varies as a function of temperature. The aforementioned effects are due to coherence, which is present despite the broadband spectral nature of thermal radiation, and has a stronger impact for reflective materials.

1. Introduction

Radiative heat flux between two bodies at different temperatures depends on the distance separating the bodies [1]. At distances much larger than the characteristic wavelength of thermal radiation, generally estimated as being the Wien's wavelength of thermal radiation (10 μm at room temperature), the usual laws of incoherent thermal radiation – use of the specific intensity, Stefan-Boltzmann's and Wien's laws – hold. This is the incoherent far-field regime of thermal radiation, where the phases of waves can be neglected. At distances smaller than the characteristic wavelength of thermal radiation, the contribution of evanescent waves appears. When the distance between the bodies becomes very small, the heat flux due to the evanescent waves is dominant and can exceed the far-field radiative heat flux by several orders of magnitude [2–5]. This is the near-field regime of thermal radiation. A lot of attention was paid to the strong enhancement of the net radiative 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 [6,7]).

In addition, it had often been estimated that the broadband spectrum of thermal radiation does not allow observing sharp interference features. The possibility of interference behaviors for thermal radiation emission in

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the far field is experimentally known since the early 2000s, when Maruyama et al. [8] observed discrete thermal emission peaks from a microcavity array. The wavelengths of electromagnetic modes calculated by the cavity resonator model agreed with the dominant peaks. Among other surface structuring possibilities, early geometries involving gratings [9] and Fabry–Pérot layers [10] were shown to exhibit sharp peaks associated to coherence.

Is it also possible to observe coherent effects in thermal radiation transfer between two flat surfaces? The transition zone between the near-field and the classical macroscopic (incoherent far-field) regimes of thermal radiation is the focus of the present article and termed far-to-near-field transition regime. For monochromatic radiation, interference of multiply-reflected waves in the vacuum gap between two parallel plane media can lead to a decrease of the net radiative heat flux. The present article shows that a coherent far-field contribution to broadband thermal radiation (see Fig. 1(a)) can be observed in the total net radiative heat flux. A decrease of the net radiative heat flux in comparison to the far-field value, due to interferences, is possible even in this case of broadband thermal radiation. In the transition regime, near-field effects start to appear in addition to the reduction of the propagative contribution. Therefore, the total net radiative heat flux between two bodies decreases due to interferences unless the contribution of evanescent waves hides the reduction. To sum up, the interval of distances where the transition between the near-field and incoherent far-field regimes takes place involves a competition between the propagative and evanescent waves. Even though a reduction of the propagative component of radiative heat flux caused by interferences was noticeable in some simulation results in the case of two semi-infinite parallel media, including in the early work of Polder and Van Hove [2,11–13], a significant decrease of the total net radiative heat flux considering both propagative and evanescent waves could not be observed because the contribution of evanescent waves was overriding the drop caused by interferences. Let us mention that we realized recently [14] that Narayanaswamy and Mayo [15] were also working on a similar problem. In their paper [15], they focus on the radiative energy transfer due to propagating waves between two metallic half-spaces and the emphasis is on deriving useful analytical results.

In this paper, we will investigate in details the physics ruling the far-to-near-field transition and especially the coherent propagative regime of thermal radiation in the canonical case of two semi-infinite parallel media (Fig. 1 (b)). In the second section, we will briefly recall the well-known main elements of the theory used to calculate the total net radiative heat flux and the radiative heat transfer coefficient between the surfaces, as a function of material properties which are described by the dielectric constant (ε), the temperature of the media (T), and the distance (d) separating them. In the third section, the case of two gray (frequency-independent dielectric constant) identical materials will be considered for an improved understanding of the underlying physics. The propagative component of the radiative heat transfer coefficient between the surfaces will be analyzed in four typical cases depending on the relative strengths of Re[ε] and Im[ε], and on the sign of Re[ε]. Spectral and directional analyses will be conducted to describe the interference effects taking place in the cavity separating the surfaces. The dependence on temperature of the propagative and evanescent components of the radiative heat transfer coefficient will be examined as a function of the product of temperature and distance (Td). This will allow determining characteristic distances which are typical for (see Fig. 1(a)): (i) the transition between the incoherent far-field regime and the coherent far-field regime ($d_{\text{incoh-coh}}$), (ii) the distance at which evanescent and propagative waves contribute equally to the total net radiative heat flux ($d_{\text{prop-evan}}$), and (iii) the distance at which the total net radiative heat flux is minimum ($d_{\text{flux-min}}$). In Section 4, the analysis will be applied to real metallic and dielectric materials. In particular, asymptotic expressions of the propagative component of the radiative heat transfer coefficient at small and large distances will be derived for metals. Finally, it will be discussed how the temperature dependence of the dielectric function affects the present results.

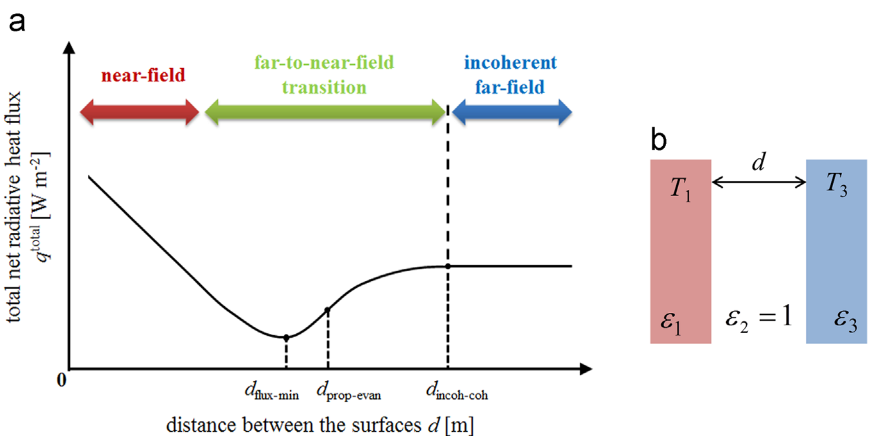

Fig. 1. (a) Schematic of the transition from the far-field incoherent to the near-field regimes. (b) Two semi-infinite parallel media at temperatures T_1 and T_3 with complex dielectric constants ε_1 and ε_3, separated by a vacuum layer of thickness d ($\varepsilon_2 = 1$).