S6 Electromagnetic proximity effects and their consequences for radiation shielding

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Did you see this?

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An outline is given of some ideas and experiments concerning proximity effects in the transfer of radiant energy between closely spaced bodies at different temperatures. Such effects can have important consequences for multiple-foil insulation. For example, when the spacing of two radiation screens is less than about $0.1/T$ cm, where T is their mean absolute temperature, an additional screen midway between them *increases* the radiation current by a factor of up to 8 X instead of reducing it by a factor of about ½.

1 Introduction

The transport of radiant energy between dissipative media at different temperatures is different from that derived from the Stefan-Boltzmann law when the bodies are closely spaced, i.e. when the spacing is less than the dominant wavelengths present. This has been shown theoretically [1–4] and confirmed by experiment [3, 5].

It has been known for some time that the density of thermal radiation in an isothermal cavity is generally less than that given by the Stefan-Boltzmann law when the dimensions are small compared with the dominant wavelengths corresponding to the temperature considered [1, 6, 7, 8, 9] (however the density may now also depend on the shape of the cavity.) This anomalous behaviour is essentially due to the cut-off of the longer wavelengths of the spectrum. It can be shown that cut-off effects also play a role in the radiative transfer between bodies at different temperatures when their surfaces have a spacing $l_c \ll \hbar c\pi/kT$ [3, 5]. A more important effect, however, arises at very small spacings: energy transfer can then take place via the evanescent field that protrudes just above the surface of the bodies.

2 Electromagnetic proximity effects

Consider two bodies with plane surfaces parallel to one another. As the spacing between the bodies is decreased, the energy transfer by travelling waves first decreases owing to cut-off effects, but this becomes compensated and soon completely dominated by the transfer of energy via the evanescent field. Electromagnetic waves are generated within a dissipative medium due to thermal agitation of the charges. Some of these waves are refracted through the surface and emitted as radiation. The waves that are internally reflected at the surface give rise to a field that protrudes above the surface and falls off exponentially but this part of the field is not responsible for emitted radiation because its Poynting vector is parallel to the surface. However, when a second dissipative medium is in close proximity to the first the evanescent field penetrates partially into the second medium, causing an absorption of energy by acceleration of the charges there.

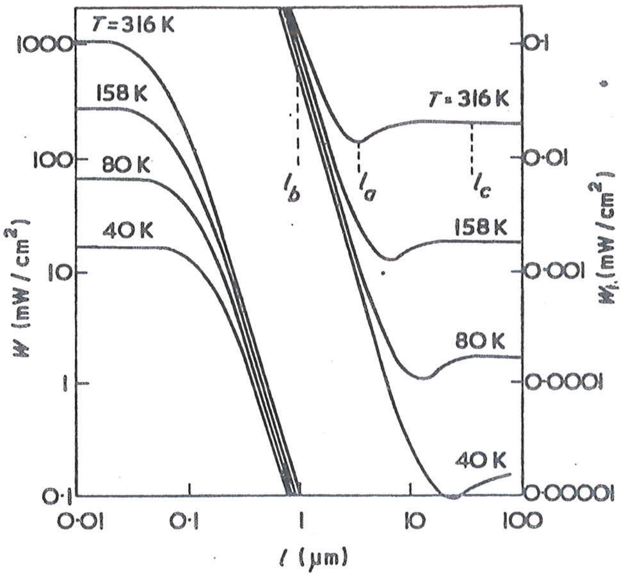

Fig.1 The total radiative transfer W between parallel surfaces of chromium, at the mean temperatures indicated, as a function of the spacing l, calculated from the theory of Polder and Van Hove. For all curves the surfaces differ in temperature by 1 K. The dielectric constant of chromium is taken to be $\epsilon \approx -i\epsilon'' = -i4\pi\sigma_0/\omega$, with $\sigma_0 = 7 \times 10^{16}$/s, a rough approximation to the data of Lenham and Treherne [10].

Measurements have been made [3, 5] which to a large exten confirm these expectations and agree well with the recent theory of Polder and Van Hove [4]. Figure 1 shows the total radiative transfer between chromium surfaces as a function of distance, calculated from the theory.

Figure 2 shows measurements of the total heat transfer between chromium surfaces near room temperature as a function of the spacing (curve 1). Naturally the travelling wave and the evanescent field contributions cannot be measured separately. Curve 2 shows the measurements after correction for various factors and curve 3 the theoretical curve within the same range of spacings. There is good agreement with regard to the distance at which the proximity effect sets in. There is also substantial agreement between the two curves at smaller spacings. The shallow minimum predicted by the theory was not, however, observed. At large distances the measurements are some 5% too high; the results of the Polder-Van Hove theory agree there with the Stefan-Boltzmann law. Figure 3 shows the

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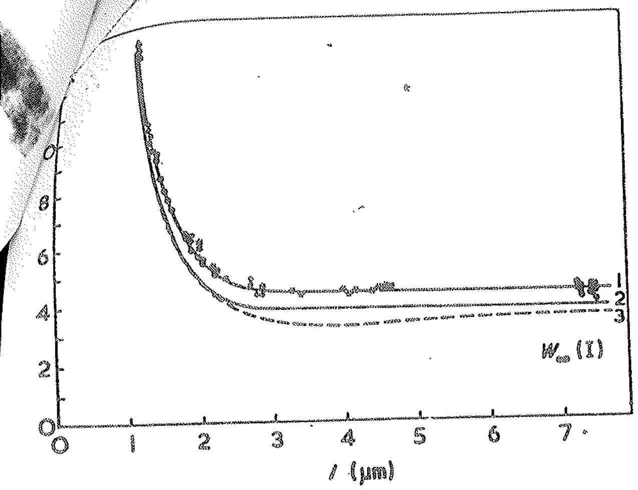

2 Measurements of the proximity effect with chro-n surfaces near room temperature, $T_A = 313$, $T_B = 295$ ve 1). Curve 2 shows these results after correction for umental errors. The theoretical results (curve 3) are ulated with the dielectric constant $\epsilon = \epsilon' - i\epsilon'' =$ $4\pi\sigma_0/(\omega_0^2 + \omega^2) - i4\pi\sigma_0\omega_0^2/\omega(\omega_0^2 + \omega^2)$, with $\sigma_0 =$ 10^{16}/s and $\omega_0 = 10^{15}$ s, a closer approximation to the ca[illegible]erties of the chromium films used. The line ked [illegible](l) is the heat transfer calculated on the basis he Ste[illegible]n-Boltzmann law. For further details, see [5].

aratus with which the measurements were performed.

mparing Fig.1 and Fig.2 it is seen that the measurements er only a small range of spacings (14 µm down to 1 µm). the lower spacings the slope of the experimental curve, en plotted logarithmically, is about −3 and is approaching value −4, the slope predicted by the theory for $l < l_b$ e Fig.1), for a metal with a large and purely imaginary electric constant. That the total heat transfer at very all spacings must vary inversely with the fourth power of e distance, can also be shown by a simple calculation [5]. r actual metals, numerical calculations show that the pe lies between −3 and −4.

is interesting to note that there is an acoustical analogue of ctromagnetic proximity effect [11]. It has been g[illegible] to use this to circumvent the Kapitza resistance at e b[illegible]ary between helium and a solid and so enhance e he[illegible]ransport across the boundary wall [12].

Consequences for multiple-foil superinsulation

n the design of multiple-foil thermal insulation it was itially assumed that the more radiation shields per unit hickness, the better would be the insulation. It was soon ound, however, in practice, that above a certain packing lensity the insulation became worse not better [13, 14]. Hitherto this has always been attributed to conduction between the radiation shields via the spacer material or via ocal contacts [14, 15]. As we show below, the radiation proximity effect is another contributory factor.

To calculate the influence of proximity effects on the effectiveness of radiation shields we need to know l_c, the distance at which these effects set in and, in particular, the value of l_b, the distance below which the total heat transfer W is proportional to l^{-4}.

The proximity effect begins to set in for $l_c \ll \hbar c\pi/kT = 0.75/T$ cm, T being the mean temperature of two radiation shields. For $T = 300$ K, therefore, $l_c \ll 25$ µm. For the value of l_b, a rough estimate is given by the distance l^* at which the slope of the curve of the travelling wave contribution is a maximum, $l^* \approx 0.15/T$ [4, 5]. The minimum in the curve predicted by the Polder-Van Hove theory lies roughly at $l_a \approx 0.1/T$. This lies at $l_a \approx 3$µm for $T = 300$ K. From Fig.1 it can be seen that a good estimate of the distance l_b, below which $W \propto l^{-4}$, is $l_b \approx 0.03/T$ cm. For $T = 300$, $l_b \approx 1$µm. At lower temperatures the values of these distances are correspondingly larger: for example, at $T = 30$ K, $l_a \approx 30$ µm and $l_b \approx 10$ µm.

In practice the radiation shields will be of metals having better reflecting properties and thus giving more effective insulation than chromium. Our calculations refer to chromium only because measurements were made with that metal.

The values of l_a, l_b and l_c are however, nearly independent of the dielectric constant of the emitting media. At cryo-

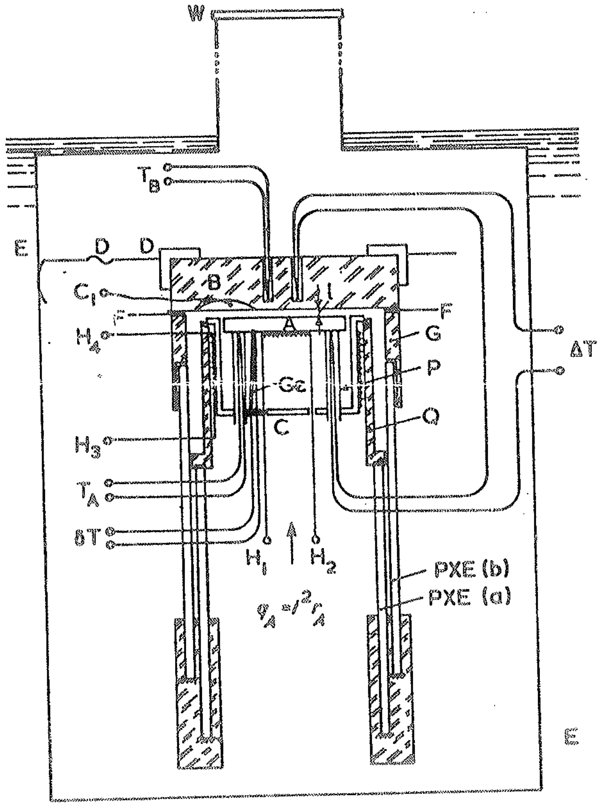

Fig.3 Apparatus for measuring radiative transfer between closely spaced plane bodies [5]. A – heated surface; B – receiver surface; C – thermal guard enclosure; D – copper ring and flexible conductors; E – vacuum vessel immersed in temperature bath; F – metal foil shims; G – glass spacers; H_1H_2 – heater for A; H_3H_4 heater for C; P – glass supporting tubes; Q – fused quartz supporting ring. T_A leads to thermistor at A, T_B leads to thermistor at B, ΔT copper-constantan thermocouple measuring $T_A - T_B$, δT copper leads to Cu-Ge thermocouple measuring $T_A - T_C$. PXE(a) are three piezo-electric ceramic tubes f or adjustment of the spacing l between A and B; PXE(b) are three similar tubes for adjustment of the orientation of B. W is a glass window (at room temperature), through which optical interference between A and B can be observed.