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THE HEAT SPREADER: SOME QUANTITATIVE RESULTS

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NOMENCLATURE

- a length parameter characterizing the width of the power input function [m]
- d thickness of poor heat-conducting layer [m]
- f function characterizing the distribution of the power input
- F Fourier transform of f, see equation (2)
- k_1 thermal conductivity of heat-spreader material [W m^{-1} K^{-1}]
- k_2 thermal conductivity of poor heat-conducting material [W m^{-1} K^{-1}]
- Q total power input of two-dimensional thermal source per unit of length of source [W m^{-1}]
- r radial direction pertinent to three-dimensional problems [m]
- ΔT temperature difference across the double layer [K]
- $(\Delta T)_0$ value of ΔT in the absence of the heat spreader [K]
- $(\Delta T)_{\text{opt}}$ value of ΔT when $\zeta_1 = \tilde{\zeta}_1$ [K]
- x lateral coordinate pertinent to two-dimensional problems [m]
- z normal coordinate [m]
- z_1 thickness of heat spreader [m].

Greek symbols

- α $\int_{-\infty}^{\infty} f(\xi)\,d\xi$
- γ ratio of thermal conductivities, k_2/k_1
- $\tilde{\gamma}$ critical value of γ (heat spreader is effective when $\gamma < \tilde{\gamma}$)
- δ dimensionless thickness of poor heat-conducting layer, d/a
- ζ dimensionless normal coordinate, z/a
- ζ_1 dimensionless thickness of heat spreader, z_1/a
- $\tilde{\zeta}_1$ optimal dimensionless thickness of heat spreader
- ξ dimensionless lateral coordinate, x/a
- ω Fourier-transform variable.

INTRODUCTION

THE PURPOSE of this note is to present some quantitative results regarding a heat-transfer device, the heat spreader, which is quite well known, and which has proved useful in various technologies. When large amounts of heat are being injected onto a restricted area of a solid body, consisting of material of relatively low thermal conductivity, the resulting thermal load could be too large. The ensuing temperature rise could cause the material to disintegrate, or otherwise lead to an undesirable condition. Should this be the case, the heat spreader offers a way out. When a layer of good heat-conducting material is placed between the heat source and the solid body, the latter will experience lower heat-flow densities and these in turn will lead to smaller temperature rises.

Laser technology is a particular context in which this device is very useful. A typical laser system consists of several layers of various materials [1, 2]. Inside one of these layers heat is being produced by electronic action. The laser itself is mounted on top of a pedestal which acts as a heat sink. In most cases this heat sink consists of copper. To obtain a suitable bond between the heat sink and the laser, only certain kinds of material can be used, and quite frequently their thermal conductivities are low. On the other hand, the temperature within the laser is not allowed to rise above a certain level, to prevent unacceptable reductions of its lifetime. Nevertheless, all the heat produced within the system has to be carried off to the heat sink by passing through the low-conductivity bond. To reduce the temperature difference across the bond, a layer of good heat-conducting material (gold) is inserted right in front of it, and this acts as a heat spreader.

It is true that most practical problems in this field are complicated by geometrical irregularities, non-uniformities of material properties and the presence of many layers. Therefore, each *given* practical case has to be dealt with by specific analytical or numerical approaches. References [1, 2] offer appropriate examples. Numerous methods dealing with heat conduction through laminated media are presented in ref. [3]. However, in the process of *designing* particular heat-transfer devices, it would be helpful to have a detailed insight into the behaviour of systems that are less complicated. As far as the heat spreader is concerned, one of the simpler systems, which still yields valuable insight, is obtained when two layers mounted on a heat sink are considered (see Fig. 1). The layer next to the heat sink is the low-conductivity one, while the second is the heat spreader.

Of course, the formal analytical solution to this heat-transfer problem has been available probably since the days of Fourier. However, a detailed examination and exposition of the parameter picture does not seem to have been given to date. As the results are by no means trivial and not without interest, there does seem some reason to present them. A fairly complete analytical treatment of this problem has been carried out elsewhere [4]. This note concentrates on some of the results, and refers to the paper mentioned above for their derivation. The temperature drop across the double layer per unit of heat input, and how it depends upon the parameters of the system, such as the thermal conductivities, the thicknesses of the layers and the lateral extent of the source is of interest.

THE TWO-DIMENSIONAL CASE

If the power distribution of the source as given by Fig. 1 does not depend upon the coordinate that is normal to both x and z,

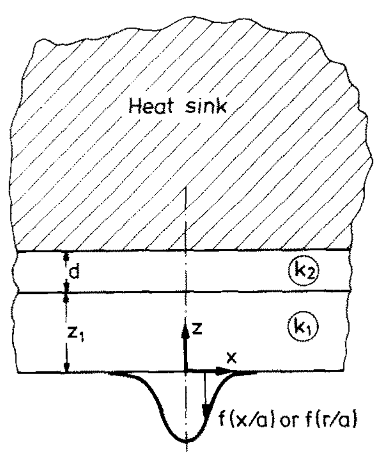

FIG. 1. Geometrical configuration showing heat spreader (k_1), heat sink and poorly conducting layer (k_2).

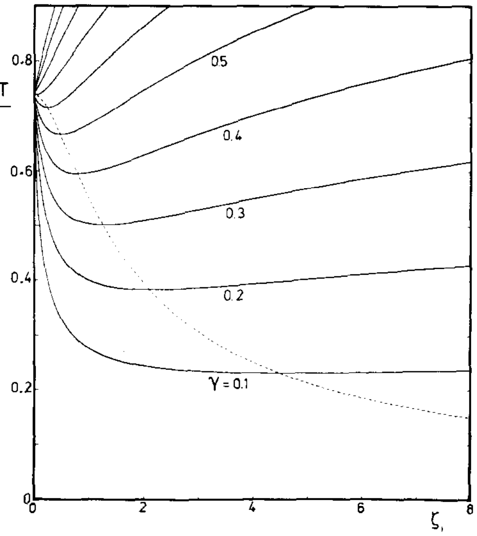

FIG. 2. Dimensionless temperature difference across double layer as a function of z_1/a and for various values of γ ($\delta = 1$). Gaussian source.

the problem is two-dimensional. It can be shown by an application of the Fourier transform that the temperature difference across the double layer is given by

$$\Delta T = \frac{Q}{\pi \alpha k_1} \int_0^\infty \frac{F(\omega)}{\omega} \frac{\tanh(\omega\delta) + \gamma \tanh(\omega\zeta_1)}{\gamma + \tanh(\omega\delta)\tanh(\omega\zeta_1)} \, d\omega, \quad (1)$$

where

$$F(\omega) = \int_{-\infty}^{\infty} f(\xi) \cos(\omega\xi) \, d\xi, \quad (2)$$

is the Fourier transform of the source distribution function f. The function f is assumed to be positive and symmetric about $\xi = 0$. As can be seen from the nomenclature, all length variables have been rendered dimensionless through division by a length parameter that characterizes the width of the source.

The parameter picture of ΔT now entails a description of its dependence upon the three parameters γ, δ, and ζ_1. Also, the effect of the shape of the source on ΔT will be of interest. Figure 2 shows the heat-spreading effect, where ΔT is given as a function of ζ_1. It shows that, when γ is small enough, an increase of ζ_1 will at first lead to lower values of ΔT. Beyond a critical value of ζ_1, which depends upon γ, and which is denoted by $\tilde{\zeta}_1$, ΔT will increase. Quite surprisingly, there is also a critical value of γ, which is smaller than unity, not equal to it, below which the heat-spreading effect can be brought about. This critical value of γ is derived in ref. [4]

$$\tilde{\gamma} = \left[1 - \frac{4}{\pi^2} \int_0^\infty \frac{\xi}{\sinh \xi} f\left(\frac{2\delta\xi}{\pi}\right) \Big/ (f(0)) \, d\xi\right]^{1/2}. \quad (3)$$

This critical value is seen to depend on the shape of the source and on δ. For instance, for a Gaussian power distribution $f = \exp(-\xi^2)$ and $\delta = 1$, $\tilde{\gamma}$ will be equal to 0.72109.

A more complete insight into the parameter dependence of ΔT is given by Fig. 3. From the RHS of this graph one may determine the value of ζ_1 at which the lowest value of ΔT is achieved. The LHS shows the actual temperature difference attained for this particular choice of parameter values. The solid lines refer to a source with a Gaussian power distribution. The dashed lines refer to $f = 1/(1+\xi^2)$. Of course, it is not always practical to choose the thickness of the heat spreader on the basis of Fig. 3. From Fig. 2 it is clear that temperature reductions that are almost as large as the optimal ones can be accomplished at values of ζ_1 that are much smaller than $\tilde{\zeta}_1$. A more detailed discussion of this matter is given in ref. [4].

CONCLUDING REMARKS

In this note it has been shown that optimal thicknesses can be chosen for thermal heat spreaders. The effect was illustrated by a few simple two-dimensional power-input distributions. Similar results can be derived for power-input functions that are symmetric about an axis and decay in all directions away from this axis. This note merely serves to draw attention to this particular device. A more detailed exposition, including both two- and three-dimensional cases, can be found in ref. [4].

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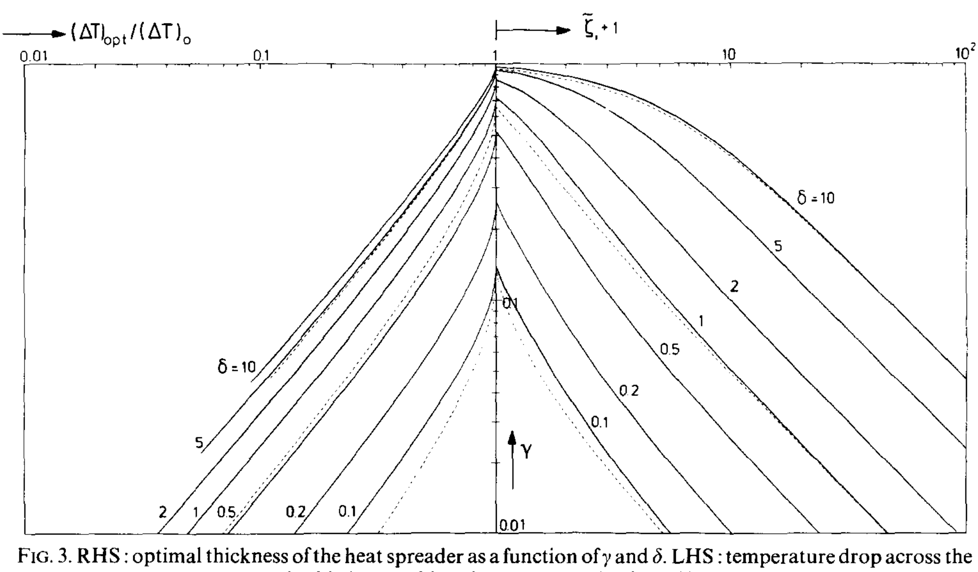

FIG. 3. RHS: optimal thickness of the heat spreader as a function of γ and δ. LHS: temperature drop across the double layer achieved at an optimal value of ζ_1.