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TEMPERATURE DISTRIBUTIONS IN PLASTIC AND IN IRON: COMPARATIVE STUDY AND APPLICATION

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ABSTRACT

The steady state temperature distribution for a plastic (poly(methylmethacrylate), (PMMA)) bar obeys a power law when heated by light, but an exponential law, as does an iron bar, when heated by a coil. The physical interpretation of this behaviour is of practical use in improving the design of solar cells.

INTRODUCTION

In the expanding field of solar energy engineering it is necessary to test various materials to improve their efficiency when used in solar cells. Two typical examples are high-purity semiconductors and plastics.

A metallic sheet exposed to the sun is heated by radiation and cooled by air convection and radiation. In principle, the way to favour the first effect over the second is to cover the sheet with some appropriate material [1]. Originally, different types of optical glass were applied to solar cells, but plastics soon started to be used [2] because of their relative advantages, such as greater flexibility, transparency, erosion resistance, and robustness. The inconvenience of a low melting point can be reduced by including certain additives in the manufacturing process. Among the more widely used plastics [3] are polycarbonate (PC), poly(ethyleneterephthalate) (PET), poly(vinylfluoride) (PVF) and poly(methylmethacrylate) (PMMA). The last is generally thought to have a longer useful life, as one experiment over eighteen years in a semi-desert location has shown [4]. There was only 10% loss of transparency which was reduced to 3% after polishing the surface, although mechanical flexibility did decline by 50%.

Previous papers studied the equations that govern the temperature distribution in metallic [5] and plastic [6] bars. In the first case, the equations for the steady state were found not to be unique but to agree mutually within statistical error, while, for the cooling, the types of equation depend on the

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temperature gradient in the bar. In the second case, the governing equations for the steady state were found to depend on whether the heating was by a coil or by radiation, while the cooling had a single solution in most of the trials. In the present paper, these general studies will be compared and then focused onto a particular aspect of the problem leading to a useful practical application in the solar energy industry.

GENERAL THEORY

Consider a straight cylindrical bar along the x-axis, with perimeter, p, and cross-section, w, that are small compared with the length, L, so that the heat flow may be considered linear. If the bar is heated from one end, the flow f_x satisfies the differential equation [7]

$$\frac{\partial f_x}{\partial x} + \rho c \frac{\partial \theta}{\partial t} + \frac{Hp}{w}(\theta - \theta_0) = A(x, t) \tag{1}$$

where ρ is the density, c the specific heat, K the thermal conductivity, H the surface conductance, $A(x, t)$ the internal source of heat and θ_0 is the constant temperature of the medium in which the bar is immersed. Equation (1) is the general equation of continuity in hydrodynamics with sinks and sources, and permits the following simplifications, depending on the problem under consideration:

(a) If the material of the rod is homogeneous and isotropic, the thermal conductivity is independent of temperature and the heat flow is given by

$$f_x = -K\frac{\partial \theta}{\partial x} \tag{2}$$

(b) If the steady state is being studied, the temperature distribution is independent of time

$$\frac{\partial \theta}{\partial x} = 0 \tag{3}$$

(c) If the material of the rod is insulated, there is no radiation into the medium and the term proportional to the surface conductance is zero

$$\frac{Hp}{w}(\theta - \theta_0) = 0 \tag{4}$$

(d) If there is no internal source of heat, then

$$A(x, t) = 0 \tag{5}$$

The four cases (a–d) of eqn. (1) can exist independently and conjointly. Note the two interesting cases when (a–c) are true, leading to Laplace's equation if (d) is satisfied, or to Poisson's equation if A is constant. These two equations are well known in various fields of physics, such as problems of electromagnetic potentials [8].

RESULTS

Experiments were performed for metallic (Fe) and plastic (PMMA) bars using the procedure described in refs. 5 and 6. The attention now is centred on two aspects of the problem: the effect on the plastic of heating by light, and the influence of the plastic on the metal when they are in contact.

In Figs. 1–3 are plotted three PMMA temperature distributions for the steady states that we shall call I–III. In each figure, the type of approximation (exponential or power) chosen to fit the experimental data is shown. In Figs. 1 and 2, the steady state was reached by light, in Fig. 3 by coil. The power and exponential behaviour in each figure is very clear. The power decay is sharper than the exponential decay from the beginning until about $x = 50$, but from this point to the end, the exponential values are always smaller than the power values. The experimental data tend to be closest to the power law in cases I and II and to the exponential law for case III. Thus, to a first approximation, it is possible to conclude that the steady state for PMMA obeys a power law when heated by light and an exponential law when heated by coil. This is not a trivial fact, because coil heating implies that all the conditions (a–d) apply and the plastic should therefore obey the same exponential law as in the iron bar. In radiative heating, however, only conditions (a–c) apply, whereas (d) does not, because $A(x, t)$ is different from zero. Thus, as a consequence of the internal sources of heat, the exponential law becomes a power law, leaving eqn. (1) in the form

$$\frac{\partial^2 \theta}{\partial x^2} = -\frac{A(x)}{K} \tag{6}$$

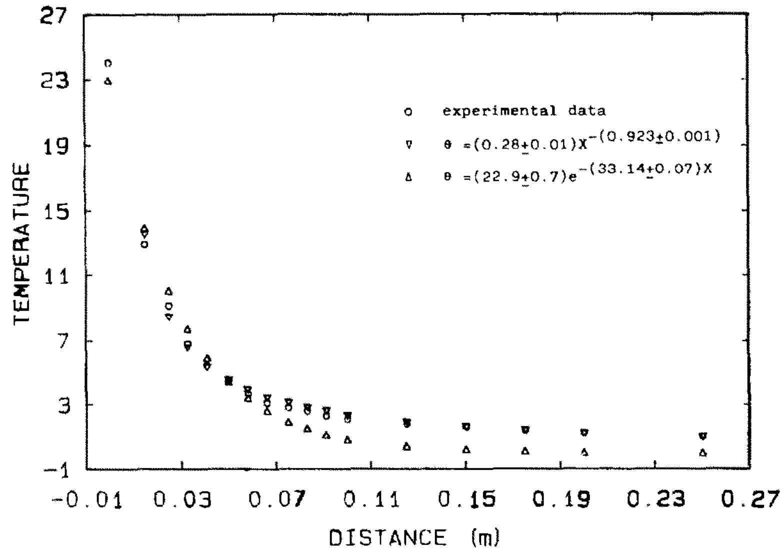

Fig. 1. Temperature distribution for steady state I, heated by light.

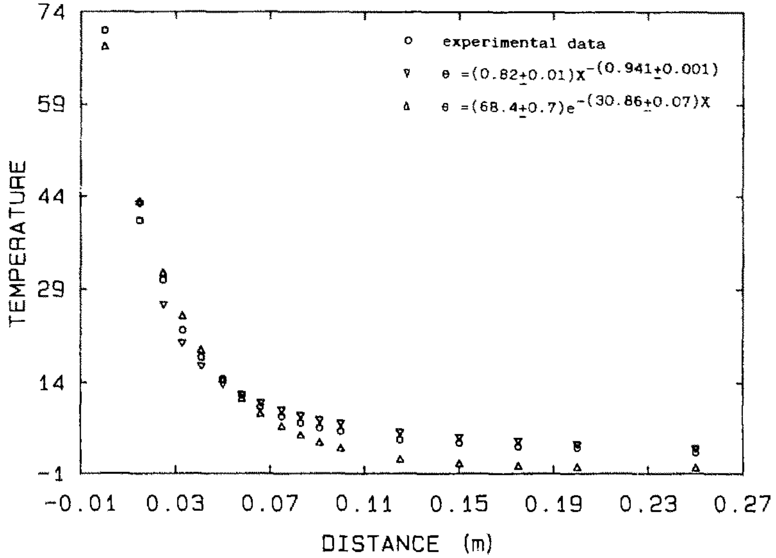

Fig. 2. The same as Fig. 1, for steady state II.

Knowing the behaviour of θ, it is possible to obtain $A(x)$ by trying different forms, starting with the crude first approximation that the heat production is independent of the temperature, or, a better approximation, supposing a linear behaviour with respect to temperature. The exact solution may of course have very different properties from these. The physical behaviour of

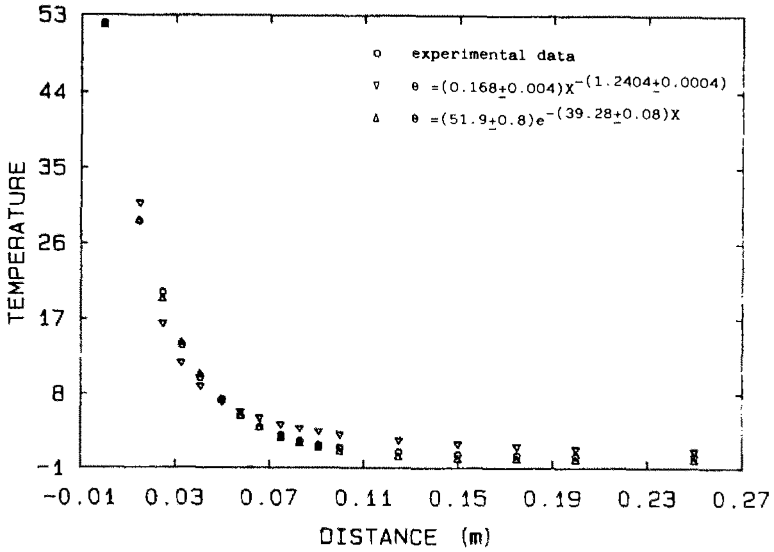

Fig. 3. The same as Fig. 1, for steady state III, heated by coil.

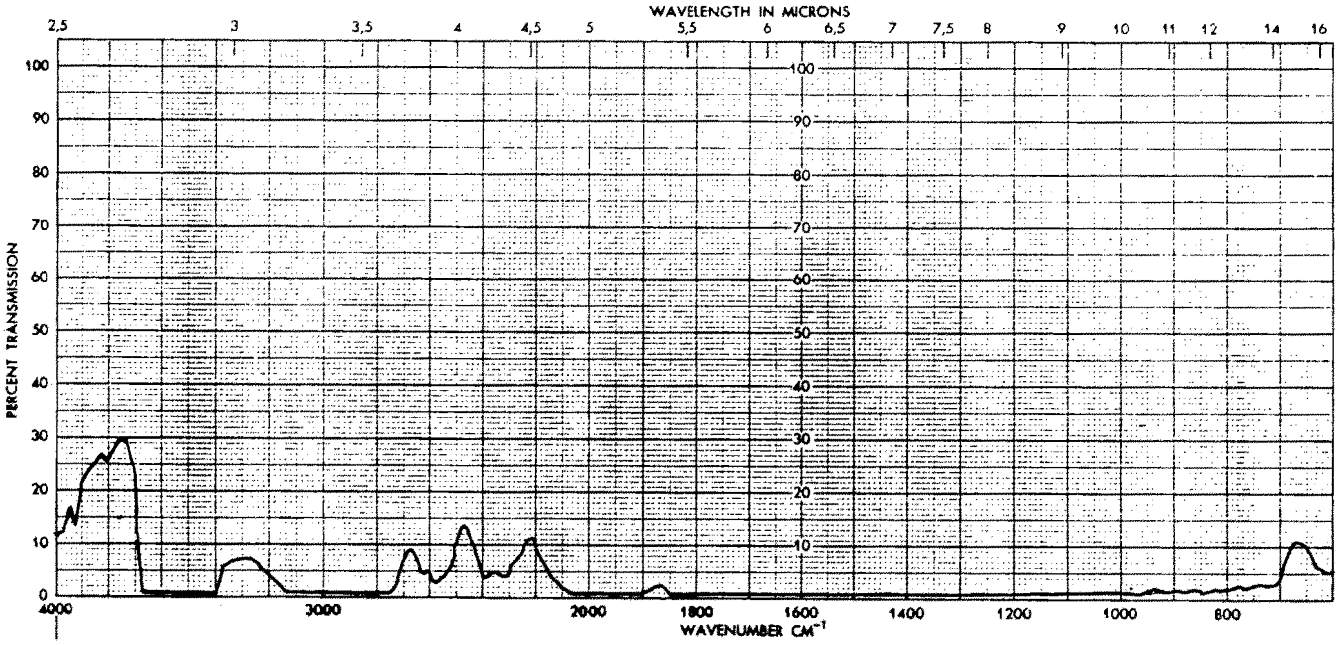

Fig. 4. Absorption for a 1 mm thick sample of PMMA as a function of wavelength.

changing from exponential to power law is easy to see in the spectral absorption of the plastic.

The lamp used in heating the plastic is usually called a 'solar lamp', because it is an attempt to reproduce the solar spectrum which is very rich in IR rays. Figure 4 shows the IR spectral absorption in a 1 mm thick sample of PMMA. Most IR wavelengths are absorbed by the plastic, and the points where the wavelengths are absorbed become internal sources of heat which is transported by conduction inside the plastic. But other IR wavelengths are transmitted, reaching about 30% transmission for a wavenumber of 3750 cm^{-1}, and there are some smaller peaks with only about 10% transmission. If a metallic film, such as iron, is placed in contact with the back of the PMMA sample, the film will heat up in two ways; by the heat conducted in the plastic and by the radiation which traversed the sample. Depending on the nature and thickness of the sample, one effect can predominate over the other, with particular combinations leading to the metallic film being heated faster or to a higher temperature.

With respect to the temperature distribution during cooling, the conditions (a), (c) and (d) are true for both materials, and the effect of the plastic on the metallic film is also favourable, as can be seen in Fig. 5. Two cylindrical samples of PMMA and iron were heated in an oven at 85 °C for 7 h. The samples, insulated with asbestos cord as described in refs. 5 and 6, were 20 cm long with a hole in the middle, drilled perpendicularly from the generatrix to the axis, where a thermocouple was inserted. Figure 5 shows the cooling for the samples after the main part of the thermal inertia of the PMMA had disappeared (the tail of this can be seen at the beginning of the

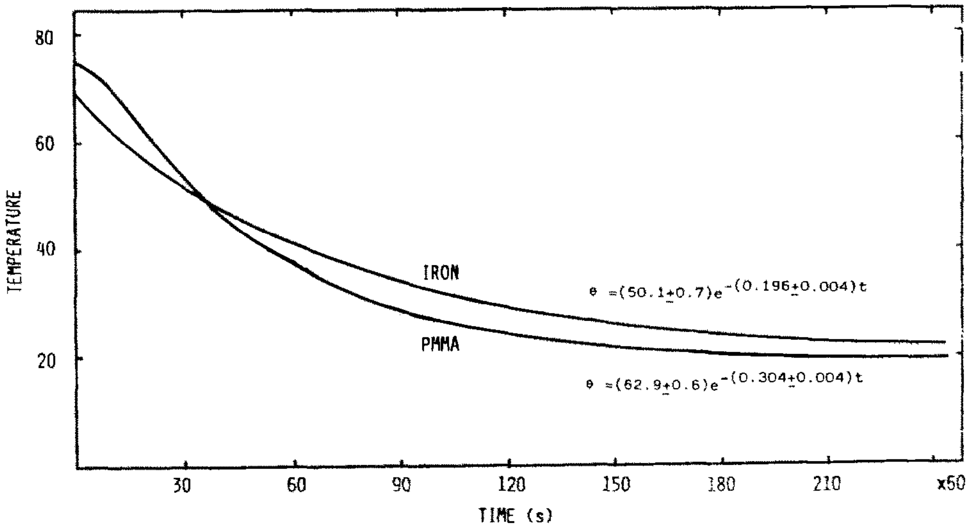

Fig. 5. Cooling curves for Fe and PMMA heated in an oven.

plot). The quicker cooling of the plastic, starting from a higher temperature than the iron and crossing over after about 40 min can be seen. This behaviour for the PMMA can protect the smoother cooling of the iron, partially preserving it from cooling by air convection, if the two materials are placed in contact, as is the case in the construction of solar cells.

DISCUSSION AND CONCLUSIONS

Some reasonable assumptions have been made in this study based on the mathematical simplicity of the problem, range of temperature used and practical applications.

The assumption for the iron bar was to consider a single exponential law for the temperature distribution in the steady state and during cooling, because the other solutions for the steady state are more complex and they give the same results (within statistical error). A double exponential solution for cooling tends to a single exponential in the range of temperatures used. The inverse fourth-power law of cooling is better than the single exponential for higher temperatures, but as the maximum temperature reached was about 70 °C, it did not dominate appreciably over the single exponential behavior.

With respect to the PMMA bar, the assumption was to consider a power law for the steady state when light is used and an exponential law when a coil is used. The steady state really satisfies a double exponential, but this accuracy over the power or exponential laws does not compensate for the difficulty of handling the four coefficients of the double exponential. However, there are significant and qualitative differences between the power and exponential laws, as we have seen.

With these assumptions, a physical justification has been found for the plastic covering on the metallic surface in order to increase the efficiency of solar cells. The justification has been tested and the explanation is based on the generation of internal sources of heat in the plastic when direct sunlight falls on the plastic over. Sunlight is very rich in IR rays, which are quickly absorbed in the plastic. The depth of penetration of the IR radiation depends on the plastic, this being one way to select the thickness of the covering. Every wavelength absorbed at a point is converted to an internal source of heat. The heat generated is transported by conduction to the metallic part of the solar cell. How to process this flow of heat for industrial applications is a matter for solar energy engineering.

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