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Computer and Experimental Modelling of Heat Leakage from Porous Substrates of LED Lighting Devices

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Abstract

In this paper we propose a mathematical and physical model of a porous substrate, evaluate influence of the pores size and quantity on the substrate's specific surface and present experimental results of the heat leakage kinetics by the porous substrate. Performances of the porous aluminium oxide printed circuit board with the record heat conductivity of 120 W/mK are presented.

Keywords: LED lighting device; porous substrate; physical model; printed board; heat conductivity.

1. Introduction and problem formulation

LED lamps are the lighting devices of new generation having a high light efficiency, a longevity, a small energy consumption [1,2]. They have wide application in residential and industrial illumination of buildings' interiors and exteriors, medicine advertisement etc. [3] One of their important merits is formation of a "good" light with high light quality for the user's health and mood [4]. Even now in many interiors the light quality may cause human

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depression and illnesses. Such impact of the light or its absence on human's mood and feeling is impressively described by many classical writers Ambrose Bierce.

At night, darkness, complete or partial lack of illumination actualizes in man a natural fear of the unknown, inexplicable, which is embodied in many books. This feature is significant for the Ambrose Gwinnett Bierce`s short stories, which the light sources of lamps, nightlights, candles, fireplaces, street lights, etc. do not give full illumination, generate halftones and shadows, cause light contrast, «objects "are enveloped" in black or "snatch out" a bright white flash against the background of blackness of darkness» [6]. That, in turn, will cause the characters superstitious fear of the dark, death, soul throwing, imaginative play. For example, darkness breeds fear in short stories «The Secret Of Macarger's Gulch» (1891): «*Outside these apertures all was black, and I was unable to repress a certain feeling of apprehension as my fancy pictured the outer world and filled it with unfriendly entities, natural and supernatural – chief among which, in their respective classes were the grizzly bear, which I knew was occasionally still seen in that region, and the ghost, which I had reason to think was not*» [5]. Also in Bierce`s short stories «The Death Of Halpin Frayser» (1891) and «Haita The Shepherd» (1891) the darkness of the night is the cause of horror in the souls of heroes: «*The failure augmented his terror; he felt as one who has murdered in the dark, not knowing whom nor why*» [5] and «*… the darkness was full of terrors*» [5]. The culmination of the plot in the development of action takes place at night, at dusk, in the pitch darkness, in the darkness of the enclosed room [6].

Some current problems of the LED lamps prevent to their wider application. They are as follows: light effectiveness, heat irradiation when using at various operating conditions. One of main directions to solve such problems is to reduce heat resistance of the LED lamp by application of materials with high heat conductivity and radiators with relatively small volume and mass but increased specific area of irradiating surface. Some examples of such radiators' designs are described in [7,8]. In [9,10] a computer simulation of the radiators with the sophisticated surface shape is presented. A modulated sinusoid shape instead of the typical rectangular shape of the radiator provide multi-fold increase of its heat irradiating surface and therefore its heat leakage efficiency.

Typical material in the LED lamp substrate is aluminum that is cheap and has high heat conductivity. Recently in RUSALOX Co., Russia a new material for the LED lighting device radiator has been developed that provides very good heat conductivity. The material is based on the porous aluminum oxide. This material based is widely used in printed circuit boards with high power efficient scattering. They satisfy high requirements to reliability and miniaturization in powerful LED and laser diodes, IGBT substrates, low profiled isolated DC/DC transformers, UV and IR modules substrates [11].

Main advantages of the porous aluminum oxide printed circuit boards are as follows:

- Price
- Stability of dielectric properties at different ambient conditions
- High temperature stability
- Opportunity to make large area boards
- High density of assembling
- Simple technology cycle
- Opportunity of recycling and "green" product

In this paper we propose a mathematical and physical model of a porous substrate, evaluate influence of the pores size and quantity on the substrate's specific surface and present experimental results of the heat leakage kinetics by the porous substrate.

2. The porosity modelling

One of promising methods the LED lighting device cooling is application of the radiator's material with good conductivity. The porous materials provide such property. Its specific surface is much more than the surface of the non-porous (solid) material.

A small hole absorbs the incident radiation good. The smaller is the hole diameter the higher is the absorption that targets to the unity. The radiation penetrating into the hole is incident onto the pore walls. Partially it is absorbed by the walls. If the hole size is small in relation to the pore depth the light ray is many times reflected by the walls before to exit from the hole. Owing to multiple reflections the almost all radiation is absorbed.

To simulate most efficient pore size we use a simple mathematical model. The radiator is a square plate with the side a and the cross-section height b (Fig. 1). The pore radius is R.

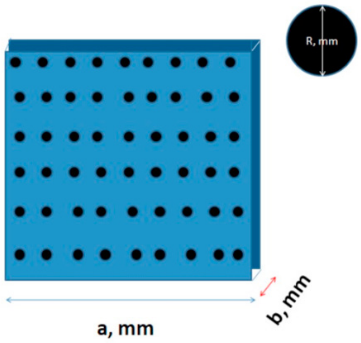

Fig.1. Substrate with holes as a model porous object.

The surface area of all the facets of the typical quadratic solid radiator is described by the simple formula:

$$S = 2a^2 + 4ab. \quad (1)$$

When the porous material with fixed pores number Z is used then the specific surface S^* is described by a formula as follows:

$$S^* = S - (2Z\pi R^2) + (2Z\pi Rb). \quad (2)$$

Dep endences of the specific surface S^* *vs* variable pore radius R at the fixed pore number Z are presented in Fig. 2. Formula (2) corresponds to a parabola with the maximum at $R = b$ (Fig. 3). That is why only left parts of the parabolic dependences at $R < b$ are presented in Fig. 2.

The more is the pores number Z the higher is the specific surface of the radiator. E. g. the 12fold increase of the Z value results in the 12fold growth of the specific surface S^* value. Most efficient is the material with the pores of the diameter of 10^{-5} – 10^{-4} m (micropores).

Therefore the porous materials have better heat resistance owing to increased specific surface in accordance with the formula:

$$R_T = \frac{\delta}{\lambda S}, \quad (3)$$

where δ is thickness of the substrate, λ is heat conductivity, S is the radiator's cross-section.

3. Porous aluminium oxide

Such simple model can explain good thermal properties of the porous aluminum oxide printed circuit boards.

Different designs of such boards with multilayer structure have been developed in RUSALOX. In a previous solution printed board IMS a copper foil is laminated onto a metal plate (e. g., Al or Cu) through a prepreg. Such dielectric layer between the metal base and the copper foil serves as a thermal interface material (TIM). In the new design the dielectric aluminum oxide layer is formed by using electrolysis and electrochemical processes without organic substances.

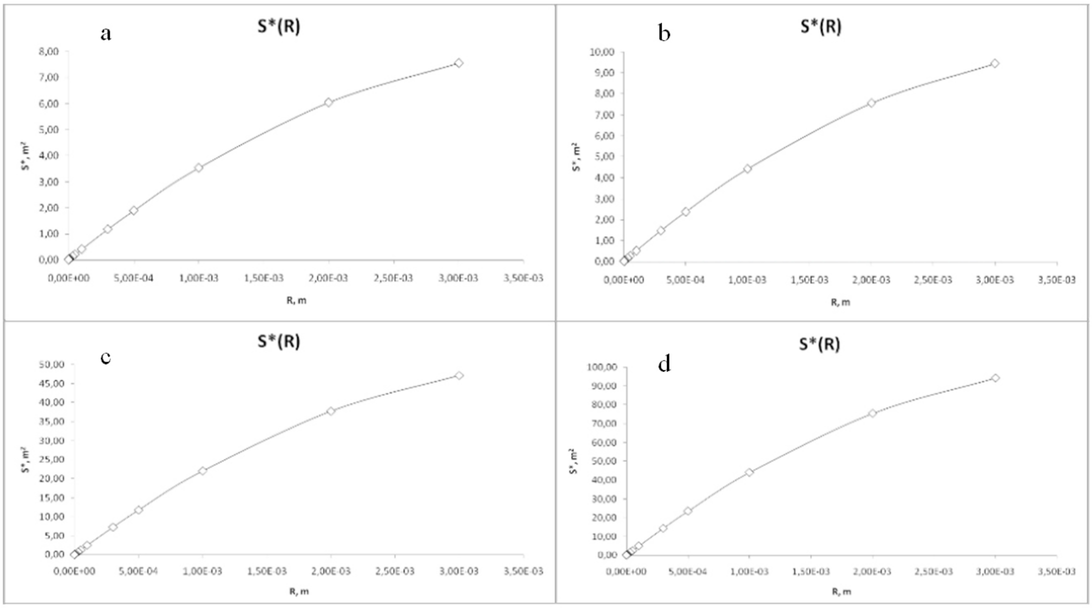

Fig. 2. Dependences of the specific surface S^* *vs* variable pore radius R at the fixed pore number Z:
(a) – 80 000; (b) – 100 000; (c) – 500 000; (d) – 1 000 000.

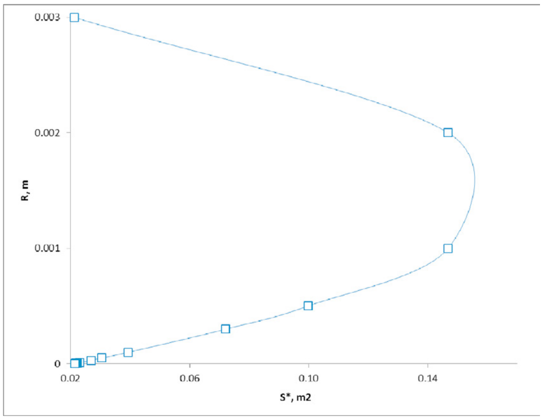

Fig. 3. Dependences of the specific surface S^* *vs* variable pore radius R.

The structure of such printed board is presented in Fig. 4.

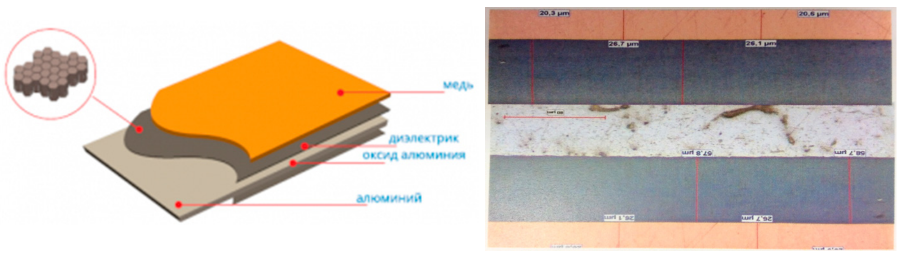

Fig. 4. Structure of the porous aluminum oxide printed circuit board.
Central grey layer is aluminium, two dark layers top and bottom are porous aluminum oxide, external layer are copper foil films.

Such printed circuit board has performances as follows [11]:

- Base thickness 0.381 mm. Thickness 1 mm and 1.5 mm is also available.
- Integral heat conductivity is 120 W/mK
- Copper film thickness is ≤ 100 μm
- Operating DC voltage 2500 V.

Cost of this material is much less than for other solutions like IMS et al.

This material (porous aluminum oxide) has also other useful applications. E. g., it was used for liquid crystal alignment [12-14]. In [15] a method is proposed to fabricate the aluminum oxide substrate and cover the pores' internal surface with an organic azo dye with the LC photoalignment properties.

The performances can be updated by using approaches developed in [16,17].

4. Conclusions

The mathematical and physical models of the porous substrate are proposed. The increase of the pores number Z results in the growth of the specific surface of the radiator as well as to reduction its heat resistance and the heat leakage improvement. Most efficient is the material with the pores of the diameter of 10^{-5}–10^{-4} m (micropores).

Experimental results of the heat leakage kinetics by the porous substrate are presented. The porous aluminum oxide substrate of RUSALOX Co. has the record heat conductivity of 120 W/mK.

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