

*Dr.Sc. Yu. E. NIKOLAENKO¹, R. S. MELNYK¹,
Ph.D. A. I. RUDENKO¹, Ph.D. S.M. ROTNER²*

Ukraine, Kiev, ¹National Technical University of Ukraine «Igor Sikorsky Kiev Polytechnic Institute»;
Odessa, ²LLC JV «LAET»

E-mail: yunikola@ukr.net

CONSTRUCTIVE AND TECHNOLOGICAL ASPECTS OF THE HEAT FLOW IMITATOR BASED ON DIAMOND-LIKE FILMS

The paper describes features of the design and manufacturing technology of a volumetric detachable heat flow imitator designed for the study of thermal characteristics and for carrying out thermal tests of heat pipes of cooling systems for electronic equipment. The authors use thin alumina ceramic plates with deposited with diamond-like films as heating elements of the imitator. Experimental results are presented on the surface temperature of heating elements and the temperature drop between the heating elements and the heat pipe in the region of the input heat flux values from 5 to 25 W. The use of the proposed heat flow imitator allows speeding up the process of research and testing of heat pipes.

Key words: heat flow imitator, diamond-like film, heating element temperature, heat pipe.

Heat pipes (**HP**) are high effective heat transfer devices for cooling systems of electrical equipment [1–4]. Testing heat pipes for compliance with the required thermal parameters and the constant development and improvement of HPs require using methods of thermal physics control and experimental investigation of the main thermal parameters of HPs, i.e. thermal resistance, maximum heat transfer ability, temperature gradient along the HP, heating zone temperature at constant heat flux, etc. During such a research, it is necessary to supply the HP with a predetermined value of the heat flux equal to the one that is generated by the electronic device being cooled. For this purpose, different heating methods and heat flow simulators are used: radiant, interface, ohmic, inductive, electronic heaters, heating by circulating coolant, etc. [5, p. 72–76].

The heat flux imitators (**HFI**) mostly used to supply heat to the HPs are electrical resistance heaters made of wire or stripe based on a material with a high electrical resistance (e.g. nichrome) coiled around HP's heating zone [6–10]. Thus, while researching glass pulsating HPs the authors of [6, 7] used high resistance wire coiled directly on the glass case (100 mm) of the HP in the heat supply zone (30 mm). The distance between the coils several times exceeded its diameter and this allows visual observing of thermal hydraulic processes inside the HP. Such HFIs are immensely simple but their design does not allow using it for testing other HPs. In [9] authors used an HFI made from high electrical resistance stripe coiled with a variable step around the 90 mm heating

zone of a glass thermosyphon 12 mm in diameter. This HFI allows obtaining a heat flux with values from 10 to 50 W. The common drawback of all considered HFIs is that it is impossible to use them in contact with electrically conductive materials. To avoid this problem, different types of high temperature isolation are used as a layer between the heater and the HP shell [9, 10]. Such designs, however, do not allow relatively easy reinstalling of the HFI from one part of the HP to the other, or to another HP.

Also well known are HFIs that consist of a metallic heat conductive base covered with electrical isolation material and coils of the stripe heater [11]. Another type of this construction is the base with mounted cartridges with the heaters [12]. For the first case, the maximum heat flux generated by HFI with a brass cylindrical base reaches 300 W [11]. For the second type of heater with five cylindrical cartridges soldered inside a copper block (with a 25×25 mm contact surface), the maximum heat flux is 628 W [12]. The maximum value of specific heat flux is up to 100 W/cm².

Very promising are the HFIs with heaters made of doped diamond-like films. Depending on the required properties of the resistive covering, one might use Cr, W, Ti, etc. as a doping metal. Due to the diamond-like structure of the film, resistive covering of such heaters has stable electrical resistance and operational thermal stability at temperatures over 500°C, specific heat flux higher than $2 \cdot 10^5$ A/cm² and temperature resistance coefficient above 10^{-4} [13].

One of the known HFIs based on a diamond-like film [14] consists of a 0.2–2.0 mm thick layer made of thermal conductive ceramics with a resistive heater on the surface. The resistive heater is made of a 0.2–2.5 μm thick doped diamond-like film with contact pads on it ends. However, the HFI with a flat contact surface is hard to use for heat flux supply to cylindrical HPs. To deal with this problem, the authors of [15] developed an HFI that is a metal cylindrical base, the surface of which is covered with a ceramic layer and a doped diamond-like film with contact pads. Near the base there is a round through hole that makes it possible to mount the heater onto the cylindrical HP. In doing so, it is desirable to leave the smallest possible split between the inner surface of the hole and the HP in order to provide a good thermal contact between the HFI and the HP. This requirement, however, is not always easy to fulfill in practice because of the following reason. Leak-tight sealing at the end-faces of aluminum HP shell is mostly made by welding the bottom cap and the bottom with a filler tube to the HP case using argon-arc welding. This process causes a metal overlap 1–3 mm in height (Fig. 1) at the place of welding, and one should avoid cutting it off mechanically, because the cut might open micropores. It is obvious that in such a case, the split between the HFI and the HP after welding might be 1 to 3 mm, which is unacceptable in the context of ensuring the heat transfer from the HFI to the HP with minimal contact thermal resistance

In this paper we present an HFI based on diamond-like films, the design of which makes

it possible to mount it with a minimal split on a cylindrical HP (or thermosyphon) with a metal overlap in welding points and to reinstall from one area of the HP to other or to another HP more easily in course of research.

Design and manufacturing process of the heat flux imitator

Let us describe characteristic features of the new design of the HFI [16] based on diamond-like films (see Fig. 2).

The base 1 of the HFI is a pipe section made from a material with a high thermal conductance (e.g., aluminum or aluminum alloys) with four (or more) flat planes 2 on the outer surface and a cylindrical hole 3 into which the HP is installed. The base consists of two parts (4 and 5) which are joined by the loop 6 with anchoring elements 7 (screws, washers and nuts). Flat heaters 8 are connected to the base planes (at least 2 heaters on each plane) through a thermal contact. The heaters are based on doped diamond-like films and have contact pads 9, which are meant for electrical contact of elements to each other and for connection to the power supply.

We shall demonstrate the technology for manufacturing HFIs of the proposed design on

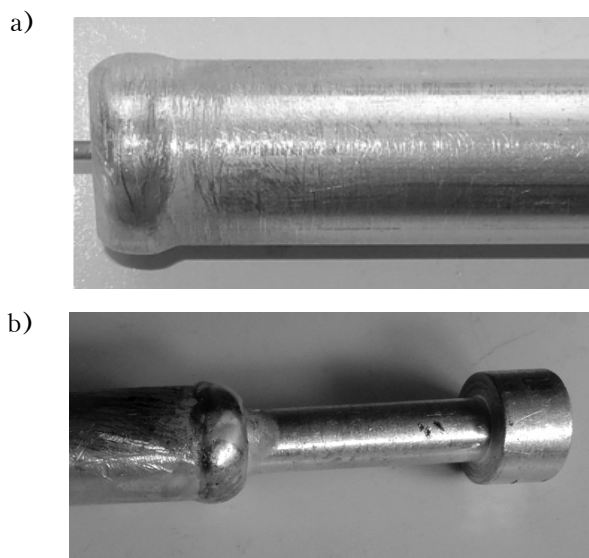


Fig. 1. Weld seams at sealing zones of the HP from the cap side (a) and from the filler tube side (b)

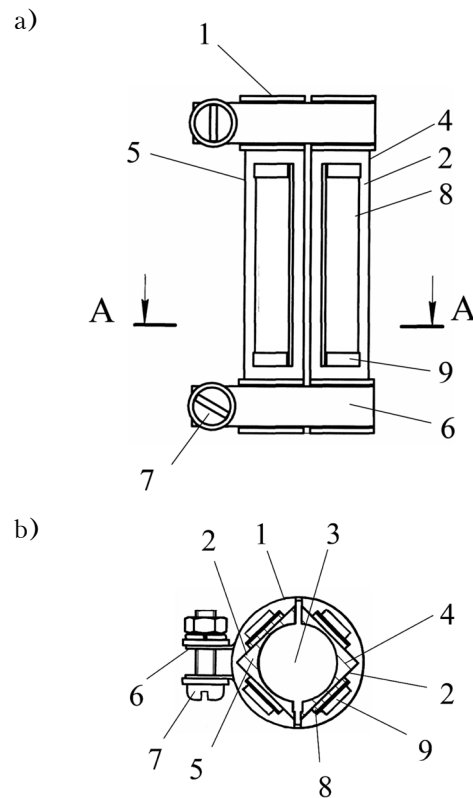


Fig. 2. HFI design: exterior view (a) and cross-section (b)

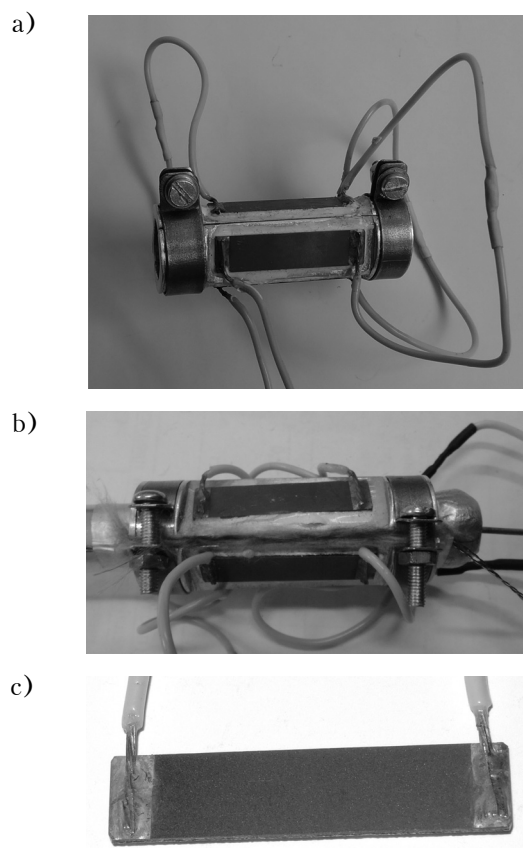


Fig. 3. Exterior view of the HFI before mounting (a) and mounted on the HP (b), and a heater based on diamond-like film (c)

the experimental HFI (**Fig. 3**). This experimental sample was made for heat supply to the HP with a 12 mm outer diameter used for LED module cooling [17].

A workpiece of the detachable base for the HFI was made from a standard pipe section with an inner diameter of 12 mm and an outer diameter of 20 mm. The material used for the base is aluminum alloy AD31T (АД31Т). Flat planes (34×13 mm) were cut out on the workpiece, and 0.5 mm deep and 6.4 mm wide grooves were lathed (these grooves were made for tightening with mounting clamps). After that, the workpiece was cut along the axis into two equal parts by a 1 mm thick disk cutter. On the inner surface of each of the parts, one longitudinal groove (1 mm wide and 1.5 mm deep) was cut for thermocouples for the HP's heating zone.

Heating elements (Fig. 3, c) were made by the JV "LAET" (СП «ЛІАЕТ», Odessa, Ukraine). Doped diamond-like films and contact pads were made using vacuum plasma-assisted deposition on 1 mm thick ceramic base according to group technology developed at the JV "LAET" [13]. The ceramic base was made of aluminum-oxide ceramics VK-94 (BK-94). The base with a diamond-like film is then cut into separate heaters (7×30×1 mm

each) by laser dicing and cutting on specialized laser equipment.

To provide thermal contact, heaters with the wires soldered to contact pads were glued to the surface of flat planes by the RTV-904 elastic silicon compound.

Method of using the HFI and research results on its thermal characteristics

To test thermal parameters of the HP with the created dismountable HFI, both its parts with attached heaters are mounted onto heating zone around the HP, then the HPs are tightened together with mounting clamps and anchoring elements. For reducing contact thermal resistance between the HP contact surface and the HFI, they are first covered with KPT-8 (KIIT-8) thermal conductive paste. To imitate the heat flux equal to the one of the electronic device being cooled, a controlled value of electrical power is fed to the HFI heaters using voltage regulator. To prevent the heat loss into the environment, the HP heating zone is insulated with basalt fibre and placed into a glass vacuum bulb.

The heat flux generated in the heaters is transferred through the elastic compound layer, which is located between the base of the imitator and the contact surfaces of the heater to aluminum base of the HFI, after which the heat power is transferred through the KPT-8 (KIIT-8) paste layer to the HP heating zone. Due to the effective heat transferring inside the HP achieved by the closed-loop evaporation condensation cycle the heat flux is transferred to the condensation zone and dissipated by natural or forced convection of air or fluid, depending on the predetermined cooling conditions.

The thermal characteristics of the created HFI sample were experimentally tested on an experimental equipment described in [16]. In the tests, an aluminum HP with a threaded capillary structure that used for the LED module cooling in the power range from 5 to 25 W. Dimensions of the HFI corresponded to those of the LED module. The diameter of the HP was 12 mm, its length was 830 mm, the length of the heating zone was 50 mm, R141b was used as a coolant. The heat was removed from the condensation zone of the HP by natural air convection at a temperature of $t_{\text{env}} = 24.0 \pm 0.5^\circ\text{C}$. The HP was orientated vertically, and the heating zone was placed below.

In the course of the experiment, the temperature t_{he} of the heating elements and the temperature difference Δt between the heating elements and the HP was measured at the heat flux values of $P = 5 - 25$ W.

The temperature of each heating element was measured by the thermocouple mounted in the middle of the diamond-like film. Thermocouple junctions were electrically isolated with glass-fibre adhesive tape. The surface temperature of the HP at the heating zone was measured by four thermocouples.

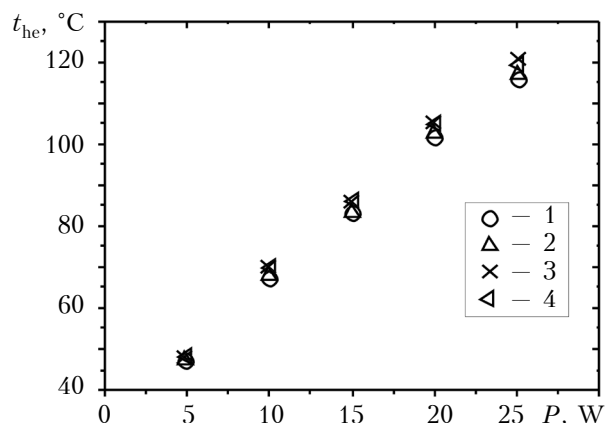


Fig. 4. The temperature dependence of the heating elements (1–4) on the heat flow of the simulator

Fig. 4 shows measured values of the temperature t_{he} of the heating elements of the HFI experimental sample for the supplied power P in range from 5 to 25 W. It is evident that the diagram is linear. Moreover, for $P = \text{const}$, the temperature of the heating elements differs by no more than 5°C. For example, for $P = 25$ W, element no 3 has a maximum value of temperature equal to 120.6°C, while element no 1 has a minimum value of temperature equal to 115.6°C. These results prove that of the contact thermal resistance values between the heating elements and the base of the HFI, as well as between the base and the HP are identical. The low temperature value of the HFI is reached due to favorable conditions of heat removal from the diamond-like film of the heating element, which in turn are caused by good thermal contact between flat surfaces. It simplifies thermal insulation conditions of the heated surfaces during the HP testing.

Fig. 5 shows the diagram for the temperature difference Δt between the average values of heating elements' temperatures (t_{he}^{av}) and the temperature in the HP heating zone relative to the supplied heat power P . As seen from the figure, as the power increases from 5 to 25 W, the temperature difference Δt increases from 3.2 to 12.0°C. While the t_{he}^{av} temperature varies from 47.3 to 118.1°C, and the difference between t_{he}^{av} and environment temperature ($t_{env} = 24^\circ\text{C}$), respectively, from 23.3 to 94.1°C. Thus, the contribution of the temperature difference Δt between the HFI and the HP temperatures in the overall temperature gradient in the cooling system is about 13%, which indicates that the overall thermal resistance of the HFI based on a diamond-like film (0.64–0.48°C/W) is rather low and that it is possible to use it to study the thermal characteristics of the HP.

Summary

The proposed design of heat flux imitator based on diamond-like films is meant for experimental

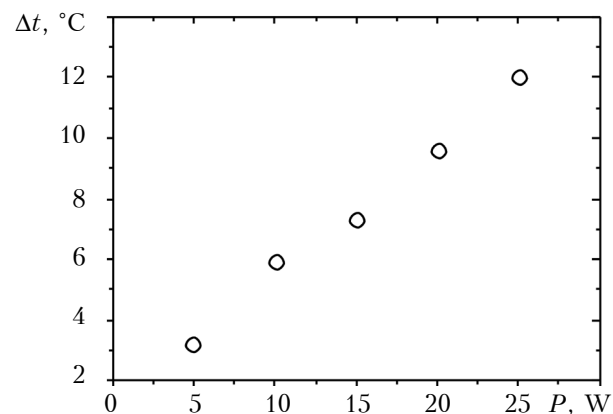


Fig. 5. Dependence of the temperature difference between the heaters and the HP on the supplied heat flux at $t_{env} = 24^\circ\text{C}$

research of thermal parameters of heat pipes. The detachable design of the imitator allows mounting it on a cylindrical heat pipe with overlaps on welding seams while providing a reliable thermal and mechanical contact. Such imitator can be easily remounted from one section of the HP to another or even to another HP altogether during tests. The imitator has a compact design that allows obtaining significant heat fluxes. For example, a heat flux of 806.67 W can be reached for a 50 mm long test sample with a hole diameter of 12 mm, with four 7×30×1 mm heaters based on diamond-like films with a total electric resistance of 60 Ohm when to a regulated power source with an output voltage of up to 220 V.

Due to the listed features, the proposed design of the heat flux imitator has a wider exploitation potential in comparison to the existing analogues.

REFERENCES

1. Khayrnasov S.M. [Application of heat pipes in the systems providing thermal conditions REA: current state and prospects]. *Tekhnologiya i Konstruirovanie v Elektronnoi Apparature*, 2015, no. 2-3, pp. 19-33. (Rus). <https://doi.org/10.15222/TKEA2015.2-3.19>
2. Baturkin V.M., Nikolaenko Yu.E., Galyautdinov D.M., Vladimirov I.T. [Effective cooling of powerful super high-frequency microelectronic unit]. *Tekhnologiya i Konstruirovanie v Elektronnoi Apparature*, 2007, no. 3, pp. 46-50. (Rus).
3. Masataka Mochizuki, Thang Nguyen, Koichi Mashiko, Yuji Saito, Tien Nguyen, Vijit Wuttijumnong. A review of heat pipe application including new opportunities, *Frontiers in Heat Pipes (FHP)*, 2011, vol. 2, 013001. pp. 1-15. <https://doi.org/10.5098/fhp.v2.1.3001>
4. Nikolaenko Yu.E., Bykov E.V., Lozovoy M.A., Khayrnasov S.M., Khmelev Yu.A. [Ways to reduce the temperature of the crystal LED in the chandelier with aluminum heat pipes]. *Proceedings of the XV International Scientific and Practical Conference «Modern Information and Electronic Technologies»*, Ukraine, Odessa, 2014, vol. 2, pp. 24-25. (Rus). <http://ela.kpi.ua/handle/123456789/17475>
5. Ivanovskii M.N., Sorokin V.P., Chulkov B.A., Yagodkin I.V. *Tekhnologicheskie osnovy teplovykh trub* [Technological bases of heat pipes]. Moscow, Atomizdat, 1980 (Rus).
6. Zhi Hu Xue, Wei Qu. Experimental and theoretical research on the ammonia pulsating heat pipe: the new full visualization of the flow pattern and the operating mechanism, *International Journal of Heat and Mass Transfer*,

2017, vol. 106, pp. 149-166. <https://doi.org/10.1016/j.ijheatmasstransfer.2016.09.042>

7. Alekseyik E.S., Kravets V.Yu. [Influence of the number of turns on the heat transfer characteristics of pulsating heat pipes]. *East-European Journal of Advanced Technologies*, series: Energy-saving technologies and equipment, 2010, iss. 6/7 (48), pp. 59-63. (Rus).

8. Asirvatham L.A., Wongwises S., Babu J. Heat transfer performance of a glass thermosyphon using graphene-acetone nanofluid. *Journal of Heat Transfer*, 2015, vol. 137, pp. 111502-1-111502-9. <https://doi.org/10.1115/1.4030479>

9. L. Vasiliev Jr., M. Rabetsky, A. Kulakov, L. Vasiliev, Z. M. Li. An advanced miniature copper heat pipes. In: *Proceedings of the VII Minsk International Seminar «Heat Pipes, Heat Pumps, Refrigerators, Power Sources»*, Minsk, Belarus, 2008, vol. 1, pp. 336-344. https://www.researchgate.net/publication/255790604_An_advanced_miniature_copper_heat_pipes_development_for_cooling_system_of_mobile_PC_platform

10. Khayrnasov SM, Rassamakin B.M. Alexeek E.S., Anisimova A.A. [Performance characteristics of aluminum thermosyphons for a combined solar collector]. *Naukovi ivisti NTUU «KPI»*, 2014, no 6, pp. 42-48. (Ukr).

11. Hussam Jouhara, Anthony J. Robinson. Experimental investigation of the small diameter two-phase closed thermosyphons charged with water, FC-84, FC-77 and FC-

3283. *Applied Thermal Engineering*, 2010, vol. 30, pp. 201-211. <https://doi.org/10.1016/j.applthermaleng.2009.08.007>

12. Ji Li, Daming Wang, G. P. «Bud» Peterson. A compact loop heat pipe with flat square evaporator for high power chip cooling. *IEEE Transactions on Components, Packaging and Manufacturing Technology*, 2001, vol. 1, no. 4, pp. 519-527. <https://doi.org/10.1109/TCPMT.2010.2099531>

13. Pat. 67527 A Ukraine. [Method of obtaining a resistive coating]. S. M. Rotner, V. E. Nikitin, 2004, byul no 6. (Ukr).

14. Pat. 5311 Russian Federation. [Heater]. A.B. Elagin, S.M. Rotner, V.V. Saltykov, 1997. (Rus). http://www1.fips.ru/fips_serv1/fips_servlet?DB=RUPM&DocNumber=5311&TypeFile=html

15. Pat. 2772 Ukraine. [Heater]. C.M. Rotner, 2004, byul no 8. (Ukr).

16. Pat. 121573 Ukraine. [The simulator of the heat flow]. Yu.E. Nikolaenko, R.S. Melnik, O.I. Rudenko, S.M. Rotner, 2017, byul no 23. (Ukr). <http://ela.kpi.ua/handle/123456789/21497>

17. Nikolaenko Yu.E., Kozak D.V. [Thermal resistance of an aluminum gravitational heat pipe with a threaded capillary structure], *Tekhnologiya i Konstruirovaniye v Elektronnoi Apparature*, 2017, no. 4-5, pp. 24-31. (Rus). <https://doi.org/10.15222/TKEA2017.4-5.24>

Received 08.12 2017

DOI: 10.15222/TKEA2017.6.29
УДК 536.248

Д. т. н. Ю. Є. НИКОЛАЄНКО¹, Р. С. МЕЛЬНИК¹,
к. т. н. О. І. РУДЕНКО¹, к. ф.-м. н. С. М. РОТНЕР²

¹Україна, НТУУ «Київський політехнічний інститут імені Ігоря Сикорського»;
м. Одеса, ²ТОВ СП «ЛАЕТ»
E-mail: yunikola@ukr.net

КОНСТРУКТИВНО-ТЕХНОЛОГІЧНІ ОСОБЛИВОСТІ ІМІТАТОРА ТЕПЛООВОГО ПОТОКУ НА ОСНОВІ АЛМАЗОПОДІБНИХ ПЛІВОК

Описано особливості конструкції і технології виготовлення об'ємного рознімного імітатора теплового потоку, призначеного для дослідження теплових характеристик і проведення теплових випробувань теплових труб систем охолодження електронної апаратури. Як нагрівальні елементи імітатора використовуються тонкі пластинки з алюмооксидної кераміки з нанесеними на них алмазоподібними плівками. Наведено результати експериментального дослідження температури поверхні нагрівальних елементів і перепаду температури між нагрівальними елементами і тепловою трубою в області значень підведеного теплового потоку від 5 до 25 Вт. Використання запропонованого імітатора теплового потоку дозволяє прискорити процес дослідження та випробування теплових труб.

Ключові слова: імітатор теплового потоку, алмазоподібна плівка, температура нагрівального елемента, тепла труба.

Д. т. н. Ю. Е. НИКОЛАЕНКО¹, Р. С. МЕЛЬНИК¹,
к. т. н. О. И. РУДЕНКО¹, к. ф.-м. н. С. М. РОТНЕР²

¹Украина, НТУУ «Киевский политехнический институт имени Игоря Сикорского»;
г. Одесса, ²ООО СП «ЛАЭТ»
E-mail: yunikola@ukr.net

КОНСТРУКТИВНО-ТЕХНОЛОГИЧЕСКИЕ ОСОБЕННОСТИ ИМИТАТОРА ТЕПЛООВОГО ПОТОКА НА ОСНОВЕ АЛМАЗОПОДОБНЫХ ПЛЕНОК

Описаны особенности конструкции и технологии изготовления объемного разъемного имитатора теплового потока, предназначенного для исследования тепловых характеристик и проведения тепловых испытаний тепловых труб систем охлаждения электронной аппаратуры. В качестве нагревательных элементов имитатора используются тонкие пластинки из алюмооксидной керамики с нанесенными на них алмазоподобными пленками. Приведены результаты экспериментального исследования температуры поверхности нагревательных элементов и перепада температуры между нагревательными элементами и тепловой трубой в области значений подводимого теплового потока от 5 до 25 Вт. Использование предложенного имитатора теплового потока позволяет ускорить процесс исследования и испытания тепловых труб.

Ключевые слова: имитатор теплового потока, алмазоподобная пленка, температура нагревательного элемента, тепловая труба.