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e-mail: panon.institut@gmail.com

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Predgovor predsjednika Upravnog odbora Panon instituta

Ideja i realizacija prvih skupova OTO započela je prije 28 godina na tadašnjem Elektrotehničkom fakulteta u Osijeku uz sudjelovanje inženjera iz Društva održavatelja Osijek (DOO). Od tada do danas skup OTO je izrastao u regionalni interdisciplinarni znanstveni skup – koji je od prvih godina organiziran u suradnji s gospodarstvom regije te Poljoprivrednim i Građevinskim fakultetom (iz Osijeka). Kako bi se održao kontinuitet - a nakon prestanka rada DOO - Fakultet elektrotehnike, računarstva i informacijskih tehnologija Osijek (FERIT) je preuzeo organizaciju ove znanstvene konferencije; tako su - uz pomoć kolega s drugih fakulteta Sveučilišta J.J. Strosmayera u Osijeku - uspješno održani skupovi OTO 2017. i OTO 2018. (u Osijeku). Na ove dvije konferencije je prezentirano 56 radova koji su prošli dvostruku recenziju Recenzentskog odbora sastavljenog od znanstvenika iz pet zemalja. Tako je organizacijski i programski načinjen značajan iskorak u odnosu na skupove iz prethodnih godina, a konferencija je dobila status međunarodnog znanstvenog skupa.

Zaključnim razmatranjima Programskog i Organizacijskog odbora OTO konferencije (na osnovu prezentiranih radova i mišljenja sudionika) ukazano je na potrebu nastavka tradicije organiziranja OTO konferencije u drugim gradovima slavonsko-baranjske regije uz snažniju zastupljenost autora iz gospodarstva. Kako se tehnologije i organizacija održavanja šire iz domene industrijske i poljoprivredne proizvodnje i na poslove održavanja komunalne infrastrukture odlučeno je da organizaciju OTO konferencija preuzme think tank „Panon“ - institut za strateške studije Osijek - uz potporu FERIT-a i Građevinskog i arhitektonskog fakulteta Osijek. Nadamo se nastavku uspješne suradnje u spajanju gospodarstva sa znanosti.

Dr. sc. Ivan Ambroš

Foreword by the President of the Board of Directors of the think tank Panon

The idea and realization of the first OTO meetings began 28 years ago at Faculty of Electrical Engineering in Osijek with the participation of engineers from the Maintenance Society Osijek (DOO). Since then, the OTO has grown into a regional interdisciplinary scientific conference - organized from the first years in cooperation with the economy of the Slavonija, Srijem and Baranja region, the Faculty of Agriculture and Faculty of Civil Engineering Osijek. In order to maintain continuity - and after the termination of the DOO - Faculty of Electrical Engineering, Computing and Information Technology Osijek (FERIT) has taken over the organization of this scientific conference; so they managed - with the help of colleagues from other faculties of University J.J. Strosmayer in Osijek – to successfully held OTO 2017 and OTO 2018 conference (in Osijek); at these conferences were presented 56 papers that have undergone a double review by a Review Committee composed of scientists from five countries. Thus, a significant step forward in terms of organization and programming compared to the meetings of previous years, and the conference was given the status of an international scientific conference.

The concluding discussions of the Program and Organizing Committee of the OTO Conference (based on the presented papers and the opinions of the participants) indicated the need to continue the tradition of organizing the OTO Conference in other cities of the Slavonija, Srijem and Baranja region with stronger representation of authors from the private sector. As the technology and maintenance organi-zation are expanding from the industrial and agricultural production domain to the maintenance of municipal infrastructure, it has been decided to take over the organization of OTO conferences by the think tank Panon - Institute for Strategic Studies Osijek - with the support of FERIT and the Faculty of Civil Engineering Osijek. We look forward to continuing the successful collaboration on connecting business with science.

Dr. sc. Ivan Ambroš

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MJERENJE TOPLINSKOG OTPORA REBRASTIH HLADNJAKA

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Professional paper

Marija Bivolčević, Tomislav Barić

Faculty of Electrical Engineering, Computer Science and Information Technology Osijek, Osijek, Croatia
E-mail: tomislav.baric@ferit.hr

Sažetak

Moderni električni uređaji često koriste poluvodiče visokih performansi kojima je rad popraćen razvijanjem znatne količine topline. Hlađenje takvih poluvodiča uobičajeno se provodi aluminijskim hladnjacima sa ili bez prisilnog strujanja zraka. Vrlo česti su slučajevi kada je potrebno mjerenjem utvrditi stvarne performanse hladnjaka. Takvi slučajevi mogu nastupiti ili kada nisu dostupni odgovarajući tehnički podatci od strane proizvođača, ili ako se mijenjaju eksploatacijski uvjeti koje proizvođač nije predvidio ili su na raspolaganju hladnjaci koji su vraćeni u ponovnu upotrebu nakon provedbe recikliranja elektroničkih proizvoda te za njih nisu poznati tehnički podaci. U navedenim slučajevima potrebno je utvrditi toplinske otpore hladnjaka mjerenjem. Od mjernog postupka očekuje se da bude jednostavan, mjerna oprema jeftina, a mjerni rezultati pouzdani. Jedan takav mjerni postupak predstavljen je u radu. U radu je prezentirana jednostavna i pouzdana mjerna tehnika određivanja toplinskog otpora rebrastih hladnjaka. Predstavljena mjerna tehnika ne zahtjeva skupocjenu opremu, niti posebne kvalifikacije mjeritelja. Teorijske osnove i pripadajuća matematička podloga predstavljeni su na jednostavan, jasan i razumljiv način, a primjena pokazana na praktičnom primjeru. Dobiveni mjerni rezultati su analizirani i komentirani.

Ključne riječi: Mjerenje, Rebrasti hladnjaci, Toplinski otpor.

Abstract

Modern electrical devices often use high-performance semiconductors whose operation is accompanied by a considerable amount of heat. Cooling of such semiconductors is usually carried out by aluminum heat sinks with or without forced airflow. It is very often necessary to determine the actual performance of the heat sink by measuring. Such cases may occur either when appropriate technical data are not available from the manufacturer, or if operating conditions change that were not foreseen by the manufacturer, or if heat sinks, which are available for use, are reused after recycling electronic products and hence technical data is unknown. In these cases, it is necessary to determine the thermal resistance of the heat sink by measuring. The measurement procedure should be simple, measurement equipment cheap, and the measurement results reliable. One such measurement procedure is shown in the paper. The paper presents a simple and reliable measuring technique for determining the thermal resistance of ribbed heat sinks. The presented measuring technique requires neither expensive equipment nor specific qualifications from the measurer. The theoretical framework and the corresponding mathematical foundations are presented in a simple, obvious and understandable way, and the application is shown on a practical example. The obtained measurement results are analyzed and interpreted.

Keywords: Finned heat sinks, Measurement, Thermal resistance.

1. Introduction

Modern electrical devices such as personal computers, power amplifiers, thermoelectric heat sinks, power electronics components (exchangers, converters, inverters, regulated power supplies) etc. often use high-performance semiconductors which are accompanied by the development of a conside-rable amount of heat. Cooling of such semiconductors is usually carried out by aluminium heat sinks with or without forced airflow. There is a trend of increasing use of heat pipes in the transport of heat from the heated semiconductor to the place of its removal to the environment using aluminium heat sinks. This trend is particularly pronounced for CPU and graphics card cooling. The need for good cooling of semiconductors on which considerable heat develops has grown to such an extent that stores with electronic equipment, especially computer equipment, are extremeely well supplied with various types of very high performance aluminium heat sinks, quality thermally conductive pastes and pads, as well as other equipment for installing heat sink. There are very common cases when it is necessary to determine the actual performance of the heat sink by measuring. Such cases may occur either when appropriate technical data are not available from the manufacturer, or if operating conditions change that were not foreseen by the manufacturer or heat sinks are reused after recycling electronic products and no technical data is known. Considering of returning heat sinks for reuse after recycling electronic products, the more favorable market value compared to new heat sinks, the use of heat sinks that are returned for reuse after the implementation of recycling of electronic products is becoming more common. In these cases, it is necessary to determine the thermal resistance of the heat sink by measuring.

The measurement procedure is expected to be simple, the measuring equipment relatively cheap and accessible, and the measurement results reliable within acceptable limits of accuracy, i.e. measurement uncertainty. One such measurement procedure is presented in this paper. The paper presents a simple and reliable measuring technique for determining the thermal resistance of ribbed heat sinks. The presented measuring technique does not require expensive laboratory equipment, nor special qualifications of the surveyor. The theoretical foundations and the accompanying mathematical basis necessary for understanding the presented measuring technique are presented in a simple, clear and understandable way, and the application is shown on a practical example of determining the thermal resistance of a finned heat sink. The measuring circuit (measuring arrangement) is shown and described with a list of measuring equipment required for this type of measurement. The obtained measurement results were analyzed and commented. The paper shows the simplicity of the presented measuring procedure, and indicates its applicability to other types of heat sinks.

2. Heat sink designs and trends

Heat sink is by nature a passive heat exchanger whose purpose is to transfer developed heat from the electrical component into the surrounding space. The materials from which they are made are typically aluminium and its alloys, and rarely copper. They are virtually non-perishable components and easily return to reuse after the electrical components are recycled. They are made in a wide range of physical dimensions and shapes (Figure 1, [1-3]). Those of smaller dimensions typically use for cooling semiconductors such as transistors, low power integrated circuits and laser diodes. Moreover, those of larger physical dimensions use for cooling semiconductors that develop significant amounts of heat such as amplifier output stages, semiconductors in power electronics circuits (rectifiers, voltage regulators, inverters), thermoelectric heat sinks, and a particularly prominent place have main processors in personal computers and high-performance graphics cards.

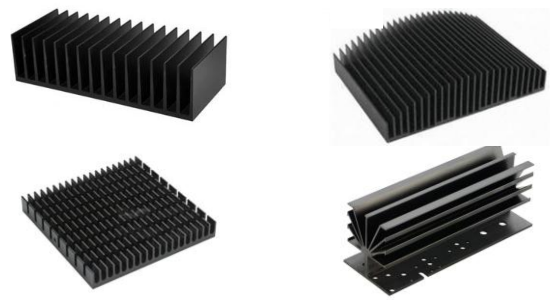

Figure 1. Some of the designs of ribbed heat sinks

Although the trend of using higher performance heat sinks is present in almost all branches of electronic products, it is particularly pronounced in certain branches, and data indicating trends are well recorded and easily accessible. For example, it is probably easiest to observe trends in the use of ever higher-performance heat sinks in the computer industry. For this purpose, let us use Table 1 [4] as an example, which summarizes the thermal design power (TDP) data developed by selected examples of Intel's main processors in personal computers in the period from twenty years ago to the present day.

Table 1. List of arbitrarily selected Intel processors over a period of twenty years

Processor name	Pentium III	Core 2 Duo	Core i9-9990XE
Year of appearance	1999	2007	2019
Operating frequency	600 MHz	2 GHz	4 GHz
TDP*	35 W	65 W	255 W

* *The thermal design power* (TDP) is the maximum possible amount of heat that a given component can generate under any circumstances.

3. The estimation of thermal resistance

To estimate the thermal resistance of a particular heat sink for which no technical data are known, technical data of geometrically similar heat sinks are useful. In doing so, attention should be paid to the methodology for determining the thermal resistance of the heat sink for which the manufacturer has provided data. Firstly, this refers to the thermal resistance data at which the difference between the temperature of the heat sink and the environment is the measured. Therefore, the dependence of the heat convection coefficient (h_c) of a certain heat sink geometry in laminar airflow can be described by the empirical expression [5-8]:

$$h_c = K \cdot \left(\frac{\Delta T}{L} \right)^{0.25}, \qquad (1)$$

where: K - represents factor that depends on the geometry of the heat sink (-), ΔT - represents the temperature difference between the surface of the heat sink and the environment (K), L - represents characteristic dimension of the heat sink (m).

Although, the total thermal resistance of the heat sink is the sum of the thermal resistance due to heat transfer by conduction through the metal body of the heat sink and convection from its surface. Since the thermal resistance due to convection from its surface is much higher, with a slight error it can be approximated for the thermal resistance of the heat sink [5-8]:

$$R_{th} \approx R_{conv} = \frac{1}{h_c \cdot S}, \qquad (2)$$

where: h_c - represents convection coefficient (W/(m^2 K)), S - represents the surface area involved in heat dissipation to the environment (m^2).

In heat sinks where the transfer of heat to the environment is supported by forced airflow through the fins of the heat sink using a fan, it is much more difficult to estimate the thermal resistance value of a particular heat sink based on known technical data of a similar heat sink. Therefore, manufacturers rarely state how much air volume is expelled by the intended fan and at what fan speed. If the velocity of airflow through the heat sink fins is known, a rough estimate of the amount of heat convection coefficient can be obtained using the empirical expression [9]:

$$h_c = 12{,}12 - 1{,}16v + 11{,}6\sqrt{v}, \qquad (3)$$

where: h_c - represents convection coefficient (W/(m^2 K)), a v - represents airflow velocity (m/s).

4. Measuring arrangement

Due to the importance of the thermal resistance measuring of cooling bodies (heat sinks) and achi-eving the smallest possible measurement error, spe-cial laboratory equipment is usually used for this purpose [10]. However, for less demanding measu-rements, i.e. if an absolute measurement error up to 10% is acceptable, thermal resistance measurements can be performed with much cheaper measuring equipment. One such procedure is presented in this paper. The thermal resistance measurements of the finned heat sink described in this article were carried out as part of the final paper [11].

A metal container filled with oil inside and electric heater was used as the heat source. Considering unlike professional laboratory equipment, the gene-rated heat flow is not directed exclusively towards the heat sink to which the thermal resistance is measu-red, it is necessary to measure the thermal resistance of the container itself when the heat sink is not placed on it. Then, the thermal resistance measurement of the system formed by the installed heat sink and the container on which it is installed is approached. After the measurements, the thermal resistance of the heat sink is determined from the known data on the ther-mal resistance of the container itself and the thermal resistance of the container-heat sink system.

Laboratory equipment for conducting measu-rements are a regulated laboratory power supply, two precision thermometers, a non-contact device for measuring the fan speed and a thermally conductive pad. A diagrammmmatic representation of the measu-ring device for measuring the thermal resistance of finned heat sinks is shown in Figure 2 and photo-graphs of the measuring device during the measu-rement of the thermal resistance of the container and container-heat sink system in Figure 3 [11] and Figure 4 [11].

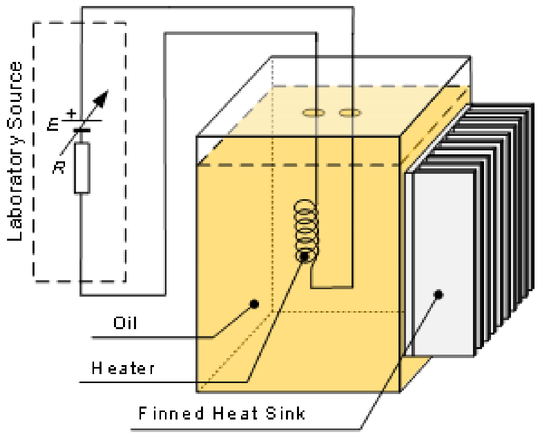

Figure 2. Diagrammatic representation of the measuring device for measuring the thermal resistance of finned heat sinks

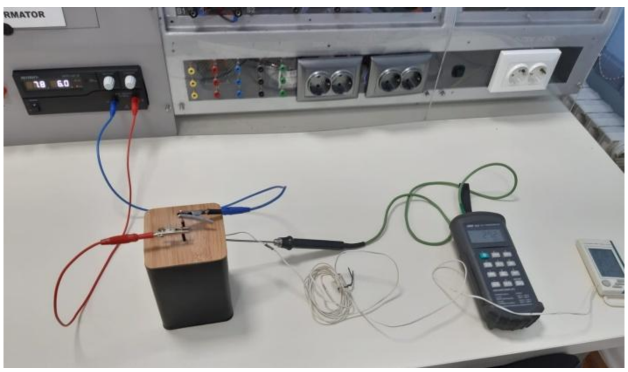

Figure 3. View of a metal container with a heater and thermometers

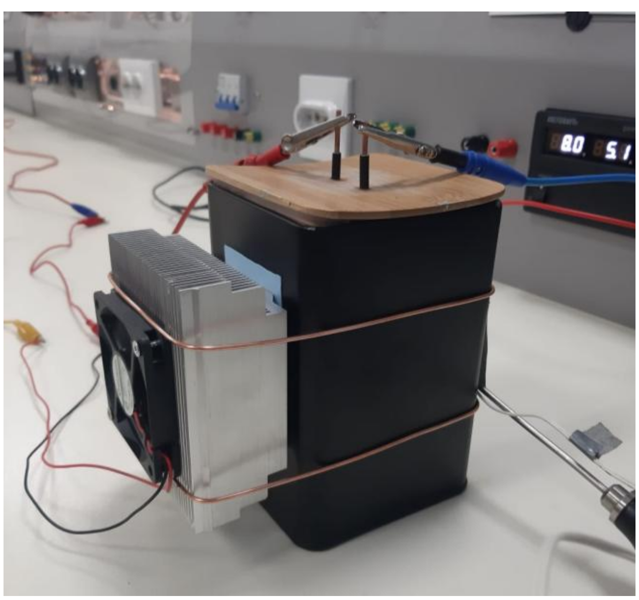

Figure 4. Metal container with heat sink and fan

5. Thermal model

Using appropriate Kirchhoff thermal schemes [5-8], thermal transients and steady states during measurements can be successfully described (Figures 5-8). The meaning of network elements and physical quantities in the schemes shown is as follows. $R_{container}$ - thermal resistance of the container due to convection of heat into the environment, $R_{heat\ sink}$ - thermal resistance of the heat sink, C_{th} - thermal capacity of the container, T_a - ambient temperature, T_s - surface temperature, $\Delta T = T_s - T_a$ - difference between surface and ambient temperature, P_h - electric power of the heater, $\dot{Q}_{in}$ - heat flow causing change internal energy, $\dot{Q}_{conv}$ - heat flow due to convection of heat into the environment.

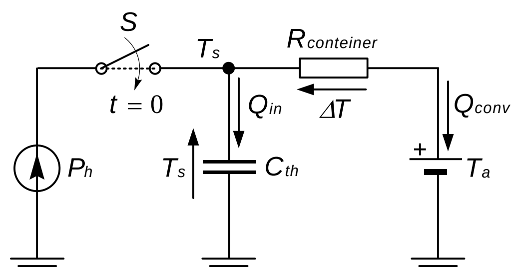

Figure 5. Transient model of heating container

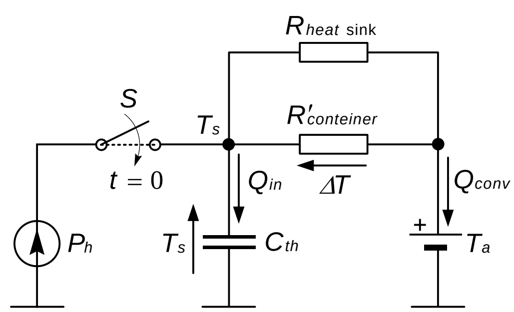

Figure 6. Transient model of heating a container with installed heat sink

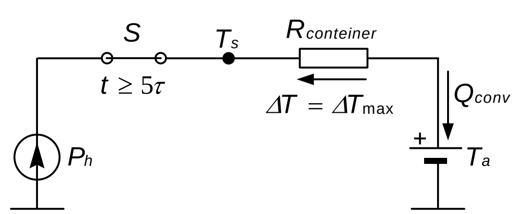

Figure 7. Steady state model of a heated container

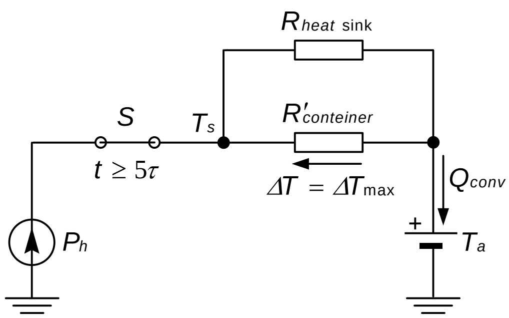

Figure 8. Steady state model of a heated container with a placed heat sink

According to the presented transient thermal models of heating the container without and with the placed heat sink (Figures 5 and 6), it follows that they can be described by the same set of equations with a difference in only understanding the meaning of convection thermal resistance.

When the heating of a container without a heat sink is modeled, it corresponds to the thermal resistance due to heat convection from the surface of the container. When the heating of a container with an installed heat sink is modeled, it is equal to the equivalent thermal resistance in parallel circuit of resistance due to heat convection from the heat sink. After switching on the heater ($t \geq 0$), the system of equations applies in both cases:

$$P_h = \dot{Q}_{\mathrm{in}} + \dot{Q}_{\mathrm{conv}} \tag{4}$$

$$\dot{Q}_{\mathrm{in}} = C_{\mathrm{th}} \frac{\mathrm{d}T_s}{\mathrm{d}t} \tag{5}$$

$$\dot{Q}_{\mathrm{conv}} = \frac{\Delta T}{R_{conv}} \tag{6}$$

As $\Delta T = T_s - T_a$, and T_a are constant, it follows that $\mathrm{d}T_s / \mathrm{d}t = \mathrm{d}(\Delta T) / \mathrm{d}t$, and the system of equations describing the thermal transient can be reduced to one equation:

$$P_h = C_{\mathrm{th}} \frac{\mathrm{d}(\Delta T)}{\mathrm{d}t} + \frac{\Delta T}{R_{conv}} \tag{7}$$

The previous equation is usually written in the form:

$$C_{\mathrm{th}} R_{conv} \frac{\mathrm{d}(\Delta T)}{\mathrm{d}t} + \Delta T = P_h R_{conv} \tag{8}$$

In the previous expression, the member with the first derivation has the meaning of thermal time constant and is usually marked with "tau", i.e. $\tau = C_{\mathrm{th}} R_{conv}$ and the member on the right side of the equals sign has the meaning of temperature in the steady state after the transition, i.e. maximum excess temperature $\Delta T_{\max} = P_h R_{conv}$.

Taking into account the initial condition according to which the excess temperature at the moment of switching on the heater is equal to zero, i.e. $\Delta T(0) = 0$ the solution of the previous differential equation is [12]:

$$\Delta T = \Delta T_{\max} \left(1 - \mathrm{e}^{-\frac{t}{\tau}} \right). \tag{9}$$

As $\Delta T = T_s - T_a$, the expression for the surface temperature is:

$$T_s = T_a + \Delta T = T_a + \Delta T_{\max} \left(1 - \mathrm{e}^{-\frac{t}{\tau}} \right). \tag{10}$$

Expression (10) describes the transient phenomenon of a change in the surface temperature of a metal container. At the end of the transient, for which it is sufficient to take $t \geq 5\tau$, the previous expression takes the value of the surface temperature $T_s = T_a + \Delta T_{\max}$, which is in line with the values that can be read directly from the steady-state models after the end of the transient heating (Figures 7 and 8).

6. Measurement results

The initial measurement determines the thermal resistance of the container when no heat sink is placed on it. In the measurement presented in this paper, the voltage at the heater connections was 7.8 V, current 6 A, and the electrical power developed by the heater was 46.8 W. The measured heating transient of the oil-filled container to steady state is shown in Figure 9 [11].

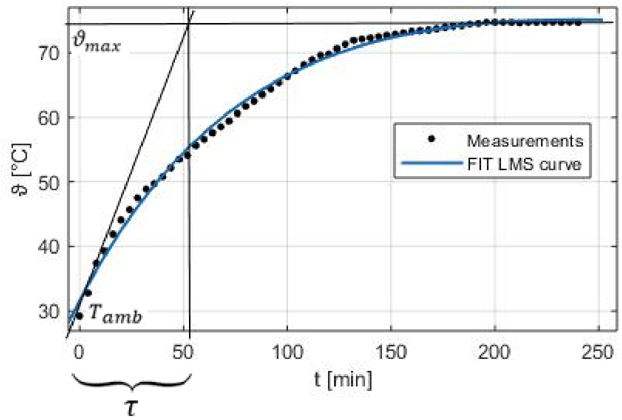

Figure 9. Measured values of the temperature at the surface of the metal container during the transient phenomenon of heating when the heat sink is not placed on it

According to Figure 9 [11], in the steady state after the heating process end, the container was heated to a temperature of = 74, 7 °C, as in this measurement the ambient temperature was = 27, 1 °C, and $\Delta T_{max} = \Delta \vartheta_{max} = 74,7 - 27,1 = 47,6$ K . Since the thermal resistance of the container is equal to the thermal resistance of the container due to convection from its surface, its thermal resistance is:

$$R_{container} = R_{conv} = \frac{\Delta T_{max}}{P_h} = \frac{47,6}{46,8} = 1,0171 \ \frac{K}{W}. \quad (11)$$

After the thermal resistance of the container itself has been determined, the next step is the measurement of the thermal resistance of the system formed by container and heat sink installed on it. In order to achieve the best possible thermal contact between the oil-filled container and the heat sink, it is necessary to place a thermally conductive pad between them and then tighten the heat sink with wires to the container.

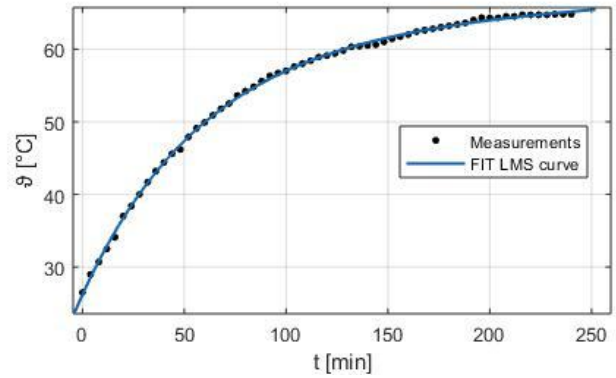

Figure 10. Measured values of the surface temperature of the metal container during the transient heating phenomenon when a heat sink without a fan is placed on it

According to Figure 10 [11], in the steady state after the heating process ends, the container and heat sink system was heated to a temperature of = 64,8 °C, while the ambient temperature was = 26,5 °C, which follows $\Delta T_{max} = 64,8 - 26,5 = 38,3$ K. In this measurement, the power of the heater was $P_h = 49,2$ W. These data allow the determination of the thermal resistance of the equivalent parallel circuit of the resistance of the container and the heat sink, which is:

$$R_{eqv} = \frac{\Delta T_{max}}{P_h} = \frac{38,3}{49,2} = 0,7785 \text{ K/W}. \quad (12)$$

Installing the heat sink on the body of the metal container, the amount of surface area of the container that participates in the heat transfer to the environment has changed. Accordingly, the thermal resistance of the container increased. Its amount can be reached by the following consideration. Prior to installing the finned heat sink, the thermal resistance of the container was determined by the expression:

$$R_{container} = \frac{1}{h_c \cdot A}. \quad (13)$$

Where: h_c -represents convection coefficient, A - represents surface of the container involved in heat transfer by convection to the environment.

Installing a finned heat sink, the area of the container participating in the heat transfer to the environment is reduced by the base area (ΔA) of the finned heat sink that rests on the container. The thermal resistance of a container with a placed heat sink is determined by the expression:

$$R'_{container} = \frac{1}{h_c \cdot (A - \Delta A)} \quad . \tag{14}$$

From the ratio of the previous two expressions follows:

$$R'_{container} = \frac{A}{A - \Delta A} R_{container} \quad . \tag{15}$$

By including numerical values:

$$R'_{container} = 1{,}1545 \text{ K/W} . \tag{16}$$

According to the transient model of heating the container with the installed heat sink (Figure 6) and the steady state (Figure 8), the total thermal resistance determined by measurement refers to the parallel circuit of thermal resistance of the heat sink and the container with reduced cooling surface. It follows that the thermal resistance of the heat sink is:

$$R_{heat\ sink} = \frac{R_{eqv} R'_{contaniner}}{R'_{container} - R_{eqv}} = 2{,}3904 \text{ K / W} . \tag{17}$$

Repeating the previously described procedure with the fan on, the measured values are shown in Figure 11 [11], and the calculated heat sink resistance values are summarized in Table 2 [11].

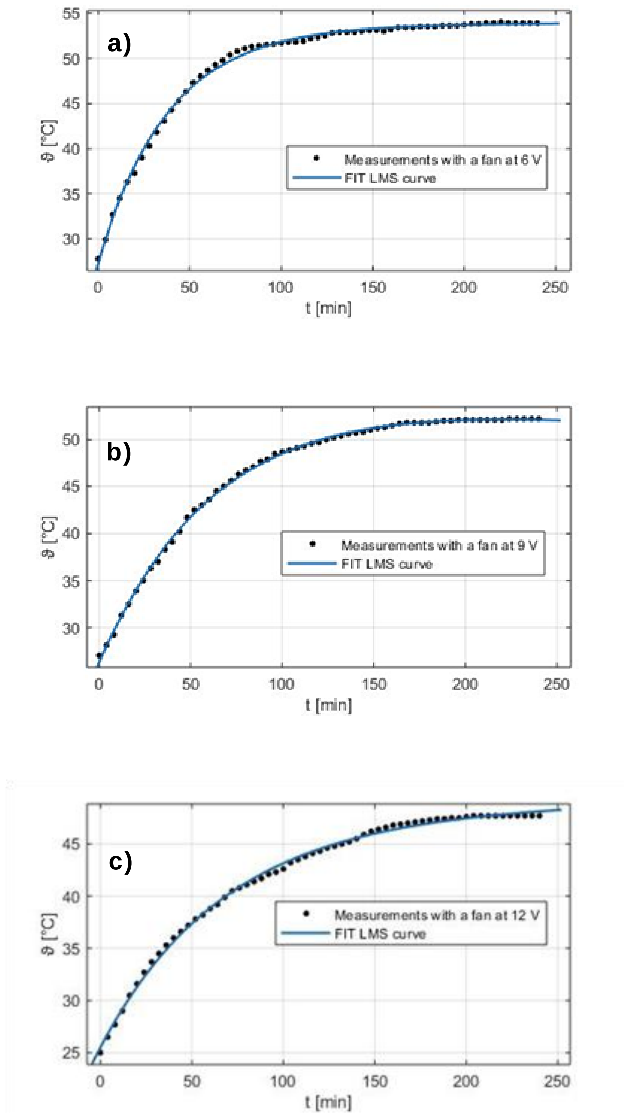

Figure 11. Measured values of the metal container surface temperature during the transient heating phenomenon when a heat sink with a fan is placed on it; the operating voltage of the fan is: a) 6 V (1510 rpm), b) 9 V (2180 rpm) and c) 12 V (2990 rpm)

Table 2. Measured thermal resistances at different fan speeds

Fan voltage [V]	Fan speed [rpm]	Thermal resistance of heat sink with a fan [K/W]
6	1510	1,0969
9	2180	1,0886
12	2990	1,0740

7. Conclusion

The article pointed out the trends in electrical engineering over the past twenty years, according to which the use of heat sinks of ever-higher performance, i.e. lower thermal resistance, is continuously growing. Meeting the market needs for such heat sinks has resulted in a rich supply and market organization. However, despite this, there are very frequent cases of very scarce technical data on heat sinks, so it is necessary to determine the amount of thermal resistance by measurement. At the same time, with the obligation to recycle electrical components and products, an affordable group of heat sinks has appeared on the market. Due to its nature, a virtually non-perishable component (if there is no built-in fan), there is an increased need to measure the thermal resistances of such heat sinks. For less demanding measurements in terms of accuracy of measurement results, one of the simplest measurement techniques for determining the thermal resistance of finned heat sinks is presented and described in detail. The presented measuring technique does not require expensive laboratory equipment, nor a special laboratory for this purpose, nor specific qualifications from the measurer. If necessary, the accuracy of the presented measurement techniques can be improved by placing thermal insulation on oil-filled container.

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