Investigation of Heat Sink Efficiency for Electronic Component Cooling Applications

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Abstract—**Research and optimisation of cooling of electronic components using heat sinks becomes increasingly important in modern industry. Numerical methods with experimental real-world verification are the main tools to evaluate efficiency of heat sinks or heat sink systems. Here the investigation of relatively simple heat sink application is performed using modelling based on finite element method, and also the potential of such analysis was demonstrated by real-world measurements and comparing obtained results. Thermal modelling was accomplished using finite element analysis software COMSOL and thermo-imaging camera was used to measure the thermal field distribution. Ideas for future research involving improvement of the experimental setup and modelling verification are given.**

Index Terms—**Finite Element Method, heat sinks, temperature measurement.**

I. INTRODUCTION

All components including capacitors, inductors and semiconductor devices which are used in power converters have maximum operating temperatures defined by manufacturer. Increased power density is the main factor which influences the thermal management to become so important. Researchers look for new methods how to increase the systems cooling efficiency and engineers try to optimize the placement of components on PCB which improves cooling possibilities as well. In modern industry, the cooling efficiency of a system is primarily determined by using numerical modelling techniques [1].

There is a wide range of numerical methods used in thermal analysis like boundary element method, finite difference method, and finite element method. Nowadays the finite element method is most widely used to analyse, simulate, optimize and design electronic devices and their systems. Most material properties are temperature-dependent, and this effect introduces multi-physics modelling, for example connecting electrics and heat transfer physics in one area. Finite element analysis software *COMSOL Multiphysics* was selected to perform modelling in our case.

II. COMPONENTS USED FOR THE EXPERIMENTS

The heat sink made by company *Wakefield Thermal Solution* was selected (Table I) [2].

TABLE I. SPECIFICATIONS OF THE USED HEAT SINK.

Standard P/N	Dimensions of heat sink, (mm)	Number of fins	Natural convection, Power dissipation [W], 60 ºC rise heat sink to ambient	Forced convection Thermal resistance at 300 ft/min, (ºC/W)
517-95AB	57.9x61x24.1	8	11 W	2 ºC/W

After heat sink selection the transistor and the diode were selected. In this work the heat sink is investigated in environments containing natural and forced convection types. From the specifications of heat sink it is known, that the dissipated power of heat sink is 11 W when the natural convection is used. Also from specifications we know that the thermal resistance is equal to 5.45 ºC/W. As it can be seen from Table I the thermal resistance of the forced convection is equal 2 ºC/W which means that the dissipated power can be 2.72 times larger than under natural convection. So, the theoretical total dissipated power can be achieved around 30 W. When the maximum dissipated power is known, the transistor and the diode can be chosen. In order to investigate the thermal management, it is better to choose the transistor with larger on-resistance value.

TABLE II. SPECIFICATIONS OF THE USED TRANSISTOR AT $T_C = 25$ ºC.

On-resistance, [ ]	Maximum continuous drain current, [A]	Operating and storage temperature, ºC	Maximum power dissipation, [W]	Thermal resistance junction to case, ºC/W	Thermal resistance junction to ambient, ºC/W	Max Drain to source voltage, [V]
0.85	8	-55 to 150	125	1	62.5	500

Of course, transistor typically dissipates much more power than the diode. In this case, when the 30 W power is required, the diode power loss almost doesn't influence the total power. Thus, transistor is the predominant power

dissipator and should be selected primarily. Both components were selected to produce the total dissipated power a little larger than 30 W.

The chosen transistor is IRF840 with TO-220 package type, produced by *Fairchild semiconductor* and the main specifications of the transistor regarding to thermal management are presented in Table II [3].

When the transistor is chosen, the diode can be selected. The diode was selected regarding to the maximum current of the transistor. The diode is 10TQ045 with TO-220 package type from *International Rectifier*. The main specifications of the diode regarding thermal management are presented in Table III [4].

TABLE III. SPECIFICATIONS OF THE USED DIODE.

Maximum $I_{F(AV)}$ at 50 % rectangular waveform and T_J=151 ºC, [A]	Maximum forward voltage drop at T_J=125 ºC and 10 A, [V]	Operating and storage temperature, ºC	Thermal resistance junction to case, ºC/W
10	0.49	-55 to 175	2

As it can be seen, the diode dissipated power could be around 2 W in this case. So, it is just few watts comparing with the theoretical total dissipated power.

TABLE IV. SPECIFICATIONS OF THE USED FAN.

Size, [mm]	Voltage rating, [V]	Current, [mA]	Consumed power, [W]	Speed, [RPM]	Air flow, [CFM]	Static pressure, [Inch-H_2O]
50x50x10	5	181	0.9	4300	11	0.11

Eventually, the DC axial flow fan was chosen from *Multicomp*. The main specifications of the fan are given in Table IV [5].

III. EXPERIMENTAL SYSTEM

The experiments and simulations were accomplished using selected transistor, diode, heat sink and fan. Additional thermal interface material (TMI) of type *MK3306-Insulating kit* from *Multicomp* was used between the transistor or diode and the heat sink and was applied to TO-220 components. The TMI is made from mica which has the thermal conductivity equal to 0.71 (W/m*K) and its dimensions are 19mm x 15 mm x 0.1 mm. The transistor and the diode are screwed to the heat sink. For experiments the thermo-imaging camera was used and all experiments were made under steady state condition. Gate to source voltage applied to the transistor is equal to 12 V.
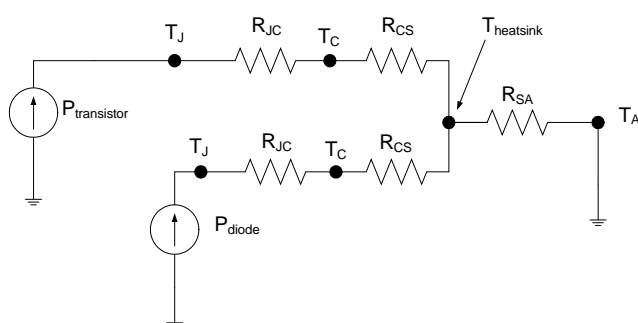
The thermal circuit of the experimental system is shown in Fig. 1, where T_J – junction temperature [ºC], T_A – ambient temperature [ºC], R_{SA} – heat sink thermal resistance [ºC/W], R_{JC} – thermal resistance of junction to case [ºC/W] which is defined by the manufacturer, R_{CS} – thermal resistance case to heat sink [ºC/W]. R_{CS} resistance is user defined and it is defined by thermal interface material which is used between component and heat sink. This resistance is very small and sometimes is neglected in the calculation. The thermal circuit is shown without resistances values, because it represents only how the resistances of the all system are interconnected. Certainly, values of some resistances are fixed and don't change in the circuit. These resistances are the junction to case and case to heat sink (TMI resistance). The ground of the thermal circuit is chosen equal to the ambient temperature.

Before experiments and simulations in *COMSOL Multiphysics* the flow rate of the fan is estimated (expressed in m/s). The radiation emissivity of the black anodized heat sink is in the range from 0.82 to 0.86 and in the emissivity for experiment setup is chosen equal to 0.85 [6]. These values have to be defined during the modeling. The same 0.85 emissivity is defined in thermo-camera.

Firstly the flow rate it is converted from CFM into m/s. The square-shaped fan has dimensions 50 mm x 50 mm.

Then LFM is estimated and the correction factor is chosen equal to 80 % which is introduced into the equation

$$LFM = \frac{CFM}{A}, \quad (1)$$

where *A* is fan area.

Value of LFM is recalculated into m/s (1.66 m/s) has to be applied when the forced convection is investigated.

Detailed experimental system modelling algorithm using *COMSOL* is given in [1].

IV. SYSTEM MODEL IN *COMSOL*

Dimensions of components are presented in [2]–[5]. Exact dimensions are used to develop the spatial model in the *COMSOL Multiphysics* [7], [8]. M3 type screw is used. The silicon chip of the transistor and the diode has dimensions 3 mm x 3 mm x 0.3 mm. In Fig. 2 the created spatial model of experimental system is presented with designated materials. The geometry model with generated finite element mesh is shown in Fig. 3. The thermal conductivities of all designated materials in *COMSOL* are given in Table V.
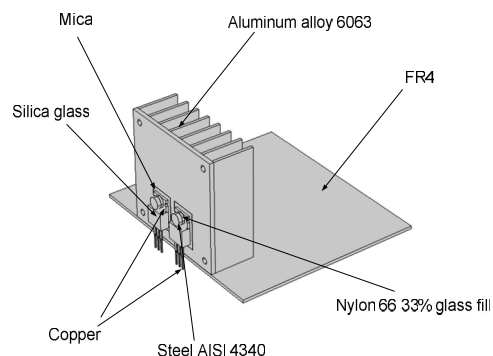

Fig. 1. Thermal circuit of the experimental system.

Fig. 2. Geometry model with designated materials.
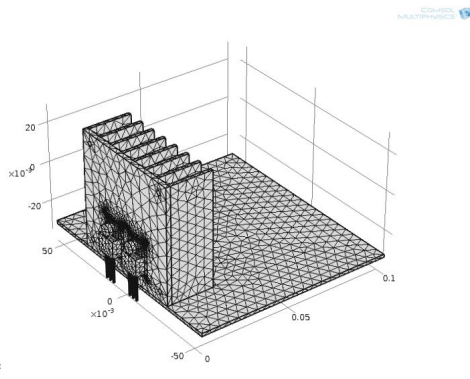
Fig. 3. Model with finite element mesh.

TABLE V. THERMAL CONDUCTIVITY OF EACH MATERIAL.

Material	Thermal conductivity (W/m*K)
Silica glass	1.38
Aluminium alloy 6063	200
Mica	0.71
Copper	400
Steel AISI 4340	54
Silicon	150
Nylon 66 33 % glass fill	0.27
FR4	0.3

Real measurements were taken when the system was placed on top of paper book; during modeling PCB made from FR4 was used as a base. Its conductivity is poor (0.03 W/m*K) and it was assumed that it doesn't influence the thermal distribution. Additional verification of thermal conductivity of different base materials should be made in future investigations.

The estimated convective coefficient is applied for vertical orientation and the radiation is used 0.85 for transistor encapsulation, heat sink, the top of the surface of PCB and bush, because they are main contributors of the radiation. It is assumed that other surfaces don't radiate the power. The average ambient temperature for all simulations cases is applied equal to 27 ℃ which is chosen from measurements with the *FLIR T200* thermo-camera. However in each case the boundary conditions can vary dependent on the situation. The variable parameter is the dissipated power of each component chip. In simulations the current is not applied to pins of the transistor and the diode (the total resistance of all pins approaches zero), because silicon chips of both components dissipate relatively a lot of power.

V. MEASUREMENTS UNDER NATURAL CONVECTION

At first measurements were made without fan. The results were measured using thermo-camera and the multimeter *AMPROBE 38XR-A*. The emissivity in thermo-camera was defined equal to 0.85. The voltage drop on the diode and the transistor was measured using multimeter.

All experiments are done when heat sink is placed on the plane as it is shown in Fig. 2. Three distances between the transistor and the diode were used (16.51 mm, 26.00 mm, 33.50 mm). The maximum temperature of the transistor reached close to 123 ℃ in all experiments.

At first analysis was performed when one heat sink outflow is covered and the distance between the transistor and the diode is equal to 16.51 mm (first case). The results are presented in Table VI. The heat sink temperature is measured at the centre of the heat sink. The results when the distance between components is equal to 26 mm are given in Table VII, and for distance equal to 33.5 mm are given in Table VIII.

TABLE VI. RESULTS WHEN THE DISTANCE BETWEEN THE TRANSISTOR AND THE DIODE IS EQUAL TO 16.51 MM.

I, [A]	$V_{transistor}$, [V]	V_{diode}, [V]	R_{ON}, [ ]	$P_{transistor}$, [W]	P_{diode}, [W]	$T_{transistor}$, [ºC]	T_{diode}, [ºC]	$T_{Heatsink}$, [ºC]
0.506	0.341	0.370	0.673	0.172	0.187	34.2	32.3	31.5
1.005	0.705	0.389	0.701	0.708	0.391	36.4	34.7	33.9
1.492	1.156	0.394	0.775	1.725	0.588	46.0	40.8	39.0
2.0	1.791	0.396	0.896	3.582	0.791	61.4	48.5	47.5
2.498	2.910	0.391	1.165	7.269	0.976	86.3	60.8	60.1
2.855	4.327	0.38	1.516	12.354	1.085	123.0	78.0	77.4

TABLE VII. RESULTS WHEN THE DISTANCE BETWEEN THE TRANSISTOR AND THE DIODE IS EQUAL TO 26 MM.

I, [A]	$V_{transistor}$, [V]	V_{diode}, [V]	R_{ON}, [ ]	$P_{transistor}$, [W]	P_{diode}, [W]	$T_{transistor}$, [ºC]	T_{diode}, [ºC]	$T_{Heatsink}$, [ºC]
0.521	0.349	0.371	0.670	0.182	0.193	33.2	31.9	31.3
1.010	0.7048	0.390	0.698	0.712	0.394	35.1	33.6	32.3
1.498	1.167	0.395	0.779	1.748	0.591	44.9	39.0	37.9
2.012	1.837	0.396	0.913	3.696	0.797	60.4	47.5	46.9
2.504	2.912	0.390	1.193	7.292	0.977	86.2	60.5	60.1
2.814	4.293	0.382	1.526	12.081	1.075	123.0	75.5	77.6

TABLE VIII. RESULTS WHEN THE DISTANCE BETWEEN THE TRANSISTOR AND THE DIODE IS EQUAL TO 33.5 MM.

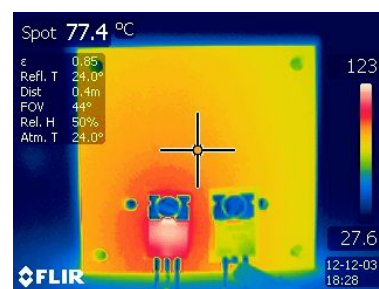| I, [A]	$V_{transistor}$, [V]	V_{diode}, [V]	R_{ON}, [ ]	$P_{transistor}$, [W]	P_{diode}, [W]	$T_{transistor}$, [ºC]	T_{diode}, [ºC]	$T_{Heatsink}$, [ºC]
0.510	0.338	0.373	0.663	0.172	0.190	33.9	32.1	30.9
1.005	0.694	0.391	0.690	0.697	0.393	35.8	33.7	32.9
1.492	1.135	0.397	0.761	1.693	0.592	43.4	38.0	37.2
1.990	1.743	0.398	0.876	3.469	0.792	58.3	46.4	45.1
2.501	2.890	0.394	1.156	7.228	0.986	86.2	59.0	59.1
2.833	4.309	0.381	1.521	12.207	1.079	123.0	74.4	77.0

Fig. 4. The temperature distribution when the distance between the transistor and the diode is 16.51 mm, one outflow covered.

Picture of thermal field measured using thermo-camera is shown in Fig. 4. The temperature increase of the diode in respect of the distance between the transistor and the diode is shown in Fig. 5. The dissipated power dependent on distance at 123 ℃ transistor temperature is shown in Fig. 6.
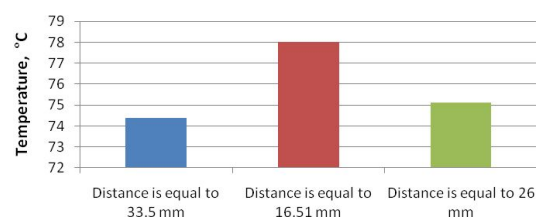

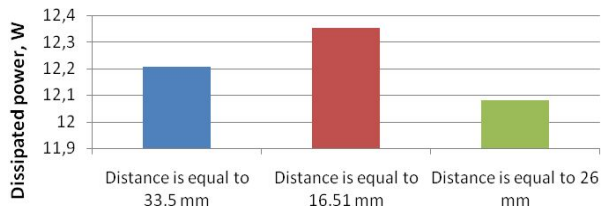Fig. 5. Temperature of the diode: dependency on distances.

Fig. 6. Dissipated power of the transistor in respect of distances from the diode.

The largest dissipated power can be achieved when the distance between components is 16.51 mm and the transistor is placed almost in the centre of the heat sink.

In simulation the heat conduction, heat convection and the radiation are used. The convection coefficient comprised of limited (between fins) and free convection is applied equal to 4 (W/m2*K). The radiation coefficient is used 0.85 as in experiments case. The dissipated power for diode is applied equal to 1.1 W and for transistor it is chosen to use 12.2 W. These dissipated powers are chosen same for all three distance values for the purpose of comparison of the temperature distribution. The result of simulation when the distance between the transistor and the diode is equal to 26 mm is presented in Fig. 7.
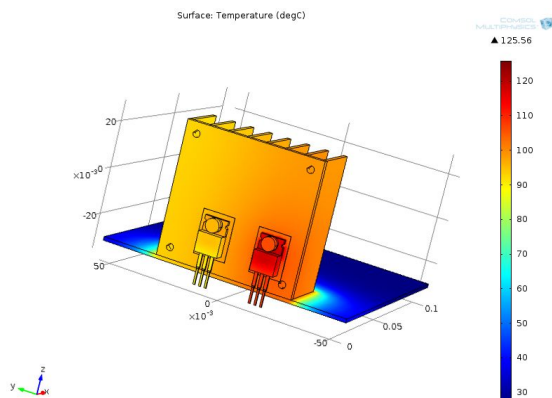

Fig. 7. Temperature distribution when the distance between the transistor and the diode is equal to 26 mm.

It was obtained that when the distance between components was 16.5 mm, the transistor temperature was the lowest (119.03 ℃) from all three simulations. In this case the heat sink can dissipate more power. When the distance was 26 mm, the temperature of the transistor was the highest (125.56 ℃), and this approximately matches real measurements. And when the distance was 33.5 mm, the temperature was equal to 123.39 ℃.
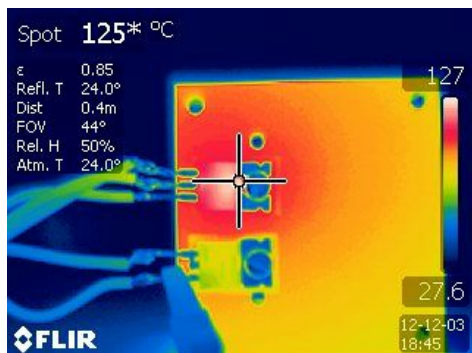

Fig. 8. Measured temperature distribution with both heat sink outflows open.

Also the experiment was made when both heat sink sides were open for airflow (Fig. 8). Firstly the maximum temperature of transistor (123 ℃) was reached and then the orientation of heat sink was changed. Then the temperature increased to 127 ℃ and current dropped from 2.855 A to 2.72 A.

VI. REFERENCE POINT OF THE TEMPERATURE AND REAL JUNCTION TEMPERATURE EVALUATION

After experiments under natural convection the reference point measurement was made. This measurement was done to find approximate value of maximum temperature of transistor chip. The temperature was compared with the thermocouple readings. The thermocouple was inserted under the screw on the transistor. The picture of the measurement setup is shown in Fig. 9.
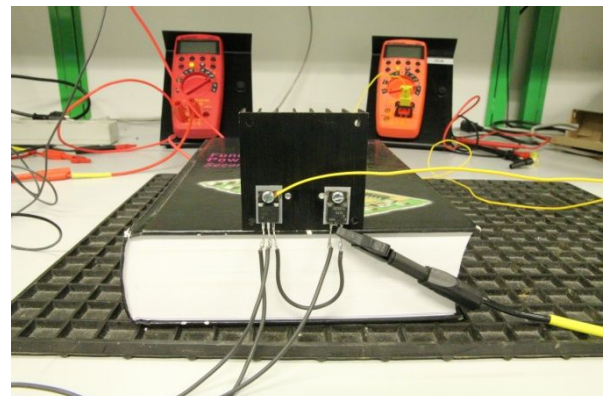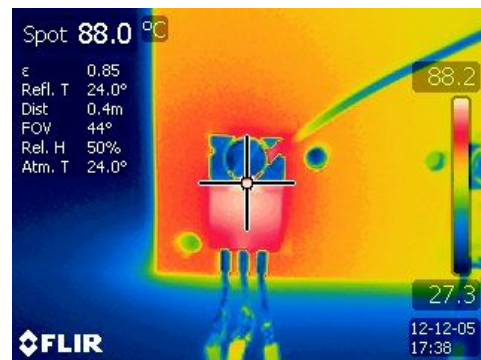

Fig. 9. Measurement of the reference point.

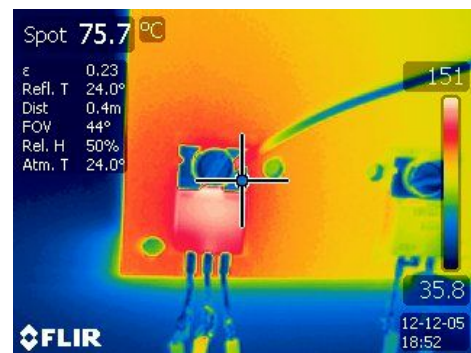Fig. 10. Measurements when emissivity is = 0.85 at the largest distance between components.

Fig. 11. Measurement of temperature on the transistor case.

The temperature of transistor case was measured when the distance between the transistor and the diode was the largest.

The current of 2.5 A was applied. It is known that the encapsulation of the TO-220 package has emissivity around 0.92 [6]. Thermal images made with the thermo-camera at different emissivity are shown in Fig. 10. The error of temperature measurements due to difference of emissivity (0.85 and 0.92) was checked for ambient temperature and maximum operating temperature of transistor encapsulation and it ranged from 2 ℃ to 5 ℃.

From IRF840 transistor datasheet it is known that the junction to case thermal resistance is equal to 1° C/W. The thermocouple mounted on the case of the transistor is very close to the chip and the maximum temperature point of the transistor. It can be assumed that the thermal resistance junction to case is the same (1° C/W) on that point. The temperature measured with thermocouple at that point was 74 ℃. In this case the dissipated power in the transistor was estimated equal to 7 W. When the necessary values are known the junction temperature can be calculated

$$T_J = 7 \cdot 1 + 74 = 81°C. \tag{2}$$

It can be seen from Fig. 11 that the reference temperature measured by thermo-camera very close to thermocouple is around to 75 ℃. The emissivity of the copper was used equal to 0.23.

VII. MEASUREMENTS UNDER FORCED CONVECTION

Measurements with fan were made when the distance between the transistor and the diode is shortest (16.51 mm), because from earlier results it could be seen that it is the best choice in order to have better thermal distribution.

Three measurement cases were selected: 1) Fan placed on top of heat sink, both sides open for airflow; 2) Fan placed on top, one heat sink air outflow side covered; 3) Fan mounted on the side of heat sink and airflow is parallel to base of heat sink.

At first the fan was attached to the top of the heat sink and for the first case the analysis was made when the heat sink base is perpendicular to airflow with one outflow covered. Firstly the maximum temperature of the transistor was reached around 123 ℃ and after that the fan was switched on. At the maximum temperature of the transistor the current reached 2.810 A. When the fan was turned on, the temperature was lowered and transistor current capacity increased until the maximum temperature (123 ℃) was reached again. The same method is used for other cases of investigation. Results are presented in Table IX.

TABLE IX. RESULTS WITH FAN WHEN HEAT SINK BASE IS PERPENDICULAR TO AIRFLOW, ONE OUTFLOW COVERED.

I, [A]	3.279	3.385	3.496
$V_{transistor}$, [V]	4.085	4.646	5.597
V_{diode}, [V]	0.426	0.424	0.422
R_{ON}, [ ]	1.246	1.373	1.601
$P_{transistor}$, [W]	13.395	15.727	19.567
P_{diode}, [W]	1.395	1.435	1.476
$T_{transistor}$, [℃]	94.3	105.0	123.0
T_{diode}, [℃]	45.2	47.1	51.0
$T_{Heatsink}$, [℃]	41	43	47

When the fan was on, the current was larger, because of the smaller on-resistance achieved due to forced cooling.

The next experiment was made when the heat sink base was perpendicular to air flow and both air outflows were open.

TABLE X. RESULTS WHEN THE HEAT SINK IS PERPENDICULAR TO AIRFLOW AND BOTH OUTFLOWS ARE OPEN.

I, [A]	3.326	3.432	3.587
Vtransistor, [V]	4.078	4.636	6.007
Vdiode, [V]	0.428	0.427	0.424
RON, [ ]	1.226	1.351	1.675
Ptransistor, [W]	13.563	15.911	21.547
Pdiode, [W]	1.422	1.465	1.521
Ttransistor, [℃]	87.7	98.2	123.0
Tdiode, [℃]	39.5	44.2	47.9
THeatsink, [℃]	40	42	46

It can be seen from Table X that applied current is a little larger than before, because we have airflow flowing through both sides of the heat sink.

The last experiment with fan was when airflow is parallel to the heat sink base, i.e. fan attached to the side of heat sink.

TABLE XI. RESULTS WHEN THE HEAT SINK BASE IS PARALLEL TO AIRFLOW.

I, [A]	3.315	3.441	3.565
$V_{transistor}$, [V]	4.167	4.801	5.595
V_{diode}, [V]	0.425	0.424	0.425
R_{ON}, [ ]	1.257	1.395	1.569
$P_{transistor}$, [W]	13.814	16.520	19.946
P_{diode}, [W]	1.407	1.459	1.515
$T_{transistor}$, [℃]	87.5	101.0	123.0
T_{diode}, [℃]	42.1	43.9	49.3
$T_{Heatsink}$, [℃]	41	45	48
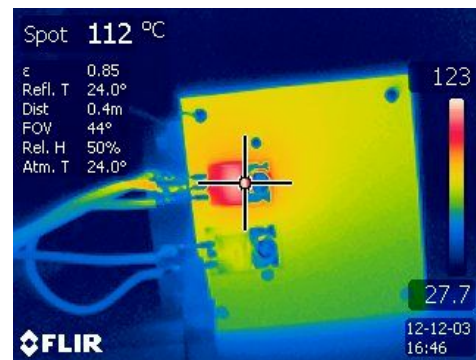
(a)
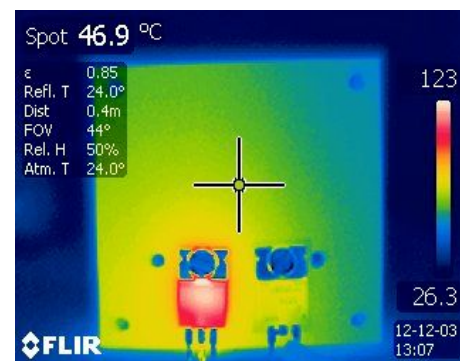
(b)

Fig. 12. Temperature distribution when airflow of the fan is: a) parallel to heat sink base; b) perpendicular to heat sink base, one outflow covered.

From Table XI it can be seen that the current is almost equal comparing with previous investigations even if the used airflow of fan is lower than in other types. It is correct

regarding theory, because the airflow is in parallel to fins and therefore can dissipate more power. Images made by thermo-camera for this are shown in Fig. 12.
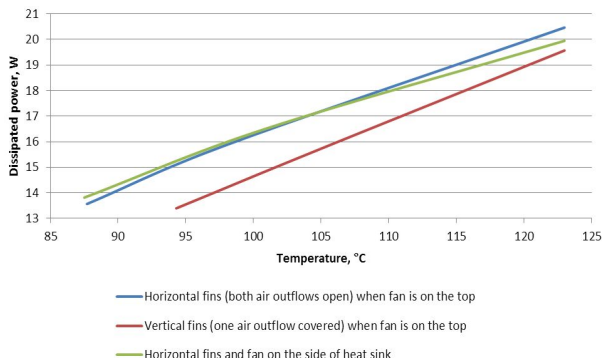

Fig. 13. Dissipated power of the transistor vs. temperature.

In Fig. 13 the dissipated power of the transistor vs. temperature of each type of experiment is shown. The dissipated powers of the diode are also not compared, because the powers are almost equal.

As it can be seen from Fig. 13, the dissipated power is the largest when airflow is perpendicular to the heat sink base and heat sink fins are horizontal.
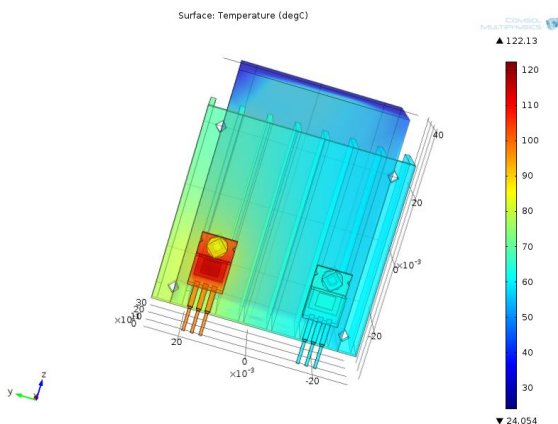

Fig. 14. Temperature distribution of the heat sink when the total dissipated power is equal to 23.5 W.

In simulation the velocity of air was applied equal to 1.66 m/s and the maximum dissipated power was selected according to measured value. Figure 14 shows the simulation results, i.e. temperature distribution when with airflow perpendicular to heat sink base and with one outflow. In simulation the PCB was not evaluated (only heat sink with the transistor and the diode). The applied dissipated power for transistor and the diode was 22 W and 1.5 W.

Since the real values of main heat sink parameters were used in simulations (dissipated power, fan air velocity), such FEM-based model with certain improvements could be used to verify the cooling capacity of different heat sink and fan combinations.

VIII. CONCLUSIONS

Three setup types with different distances between components and one or to air outflows open were investigated under natural convection. The largest dissipated power was achieved when the transistor was in the centre of the heat sink with distance between transistor and diode equal to 16.51 mm. In this case the dissipated power of the transistor was by 0.147 W larger compared to case when distance was 33.5 mm and by 0.273 W when distance was 26 mm. When the distance between components was changed, the diode temperature was by 3.6 ℃ larger compared to distance of 26 mm.

By comparing results obtained with one and two air outflows (when the temperature of the transistor reached 123 ℃ with one outflow covered) the temperature with both outflows open was 4 ℃ larger. The dissipated power was 0.64 W lower as well. This may be influenced by varied component placement locations in respect of air movement under natural convection. This factor should be investigated thoroughly in future.

Comparing the theoretical dissipated power calculation of the heat sink with the real dissipated power, in real case the dissipated power was by 2.5 W larger because in this case we also have the cooling through the plane where the components are placed. In theoretical case it is assumed that the back side of the heat sink has perfect connection with component.

In case of forced convection it was obtained that the largest power was dissipated with both outflows open and with the airflow perpendicular to heat sink base. The dissipated power of the transistor is by 0.897 W larger compared to test with one outflow covered and by 0.518 W larger compared to case when airflow was parallel to the heat sink base.

Comparing the theoretical dissipated power calculation under airflow given by manufacturer with the real dissipated power, the dissipated power was approximately 8 W less. That was due to smaller fan attached compared to heat sink specifications. The heat sink area was 1.5 times larger than area of the fan.

In future research a detailed comparison of measurement and simulation results should be performed using fine-tuned heat sink test system with minimized number of uncontrolled experimental variables, such as electronic component location in relation to the heat sink or control of ambient temperature. Also, a method for real-world verification of modelling results should be developed.

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