STUDY ON COOLING OF HIGH PERFORMANCE SIC FEATURES

VACLAV MAREK, MICHAL KRIZEK, TOMAS KAVALIR

Regional technological institute, University of West Bohemia,
Univerzitni 8, 30100 Pilsen, Czech Republic

DOI: 10.17973/MMSJ.2023_03_2022166

marekv06@rti.zcu.cz

High-performance electronic parts are vital features in almost all modern motorized machines. These silicon components are significantly minimised, especially in transportation branch. Concentration of performance requires perfect cooling conditions. A fluid flow cooling by an active cooling circuit with heat sinks is a commonly used principle. Sufficient cooling and uniform temperature field on heat transfer area are crucial parameters for the sustainable function of Silicon-Carbide components. Producer of electric vehicles induces research in the field of coolers due to the requirements of installed SiC features. This study uses advanced CFD methods to analyse the current state of commonly manufactured heat exchangers and provides new approaches by CFD optimisation in combination with 3D printed replacement parts. Approach based on 3D print also allows design inspiration in natural principles. Biomimetic inspiration shows a wide range of thousands of years lasting optimisation made by nature. Research in this field can help us with the evolution of enhanced heat transfer surfaces. Developed coolers were examined by CFD techniques. Simulations of heat transfer are verified by laboratory measurement of prototype heatsinks. These techniques are presented on the unique design of a heat sink which was simulated, manufactured, and measured. The study shows CFD approaches, describes details of prototype measurement, and also deals with negative issues of metal 3D print.

KEYWORDS

heat sink, computed fluid dynamic, flow optimization

1 INTRODUCTION

A significant amount of electric and electronic devices is placed in modern machines in all branches of mechanical engineering. A lot of traditional drive principles like compressed air or high-pressure hydraulic systems or combustion engines are replaced by electric power. Electric systems are modern, powerful, and suitable for precise drive control. Negative effects like noise, vibration, and impurity are minimised. These properties support good maintenance and user popularity in general.

Good efficiency of these drivers decrease the emit of waste heat. However, relatively low amount of waste heat is concentrated into minimised electronic silicon parts. High temperatures in precise parts like semiconductors decrease service life and increase the possibility of malfunction. These facts specify requirements for reliable and powerful cooling. [DINH 2018]

2 COOLING EFFECTS

Cooling effect is based on trivial phenomes. Heat transfer out of the semiconductor starts to throw the contact resistance between the semiconductor body and the cooler body. Contact resistance depends on contact pressure and surface quality in general [MAREK, 2016] [BERGMAN, 2011]. It can be positively influenced by contact pre-treatment by conductive paste. Silver based materials may have conductivity up to 8W/mK. The most effective materials are based on liquid metals excess 13W/mK. Heat transfer in the cooler is influenced by material conductivity and overall design. Aluminium alloys and copper is mostly used due to their excellent conductivity. Final transfer is performed by convection phenomena. Optimisation of this transfer is the main scope of this work. The radiation is almost zero. Convection transfer works with or without a forced stream of the medium. The performance of forced convection is significantly better than cooling by natural convection [2] [GOH, 2017]. The size of coolers can be minimized and heat can be transported out of the machine in case of liquid cooling circuits [BERGMAN, 2011] [MAREK, 2017].

MODEL SITUATION – SIC OPERATION

SiC parts consist of silicon and carbide. It is much more powerful than one-compound silicon features. This results in much better performance characteristics, not possible with silicon. Usage of SiC brings higher efficiency for power supplies, solar power conditioners, EV charges, etc. [ROHM, 2020]

Producer of electric vehicles for public transportation implements SiC features into power management, which requires adequate peripheries and cooling. Development of SiC, 6-port device was done.

BOUNDARY CONDITIONS

Boundary conditions of work states were defined by the producer. SiC features require maximal temperatures of contact surface 90°C, defined by customer requirements. The temperature of the environment and input cooling liquid was stated to be 50°C. The heat rate of each SiC feature was stated to be 900W. Input fluid low is 0.15-0.17l/s.

3 COOLER DEVELOPMENT

Heat transfer into liquid flow is based on heat transfer and mass flow fundamentals. A crucial parameter for heat transfer is surface area. Surface area is limited by the overall design of the cooling circuit and the design of SiC features.

BIOMIMETIC INSPIRATION

Modern CFD methods enable fluid flow optimisation concerning the maximal heat transfer, but the most comprehensive study on optimisation can be seen in nature. Nature-shaped objects can inspire the design of many special-purpose parts. Heat transfer is common phenomena in nature and natural-shaped heat exchangers can also help us with uncommon issues. Many studies show possibilities of inspiration in this field [HUANG, 2017]. The fractal shapes are high-potential ideas inspired by natural effects. Fractal shapes of natural heat transfer and mass flow can be identified in many vegetal and animal applications. These are roots of vegetation, animal blood circulation, animal body thermal management, etc. [RUPP, 2019] [KIM, 2017]

INITIAL DESIGN AND DESIGN ITERATION

Customer requirements defined input space for flow optimisation. This area is described by dimensions 35x65x5mm. This space is filled from one narrow side, and output is on another side. The initial design was simple, to be easily machined by milling tools. This can be seen in the Figure 1.

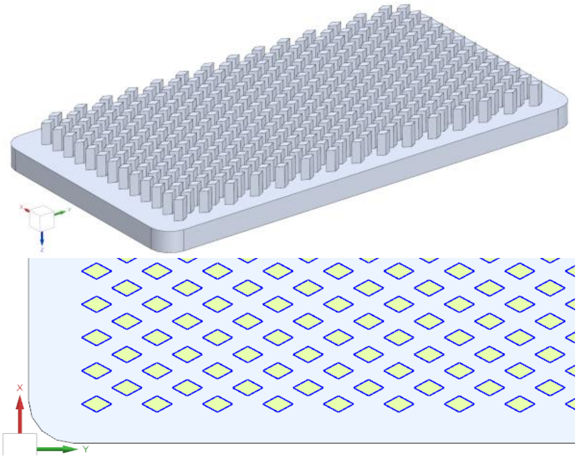

Figure 1. The initial design iteration of the cooling body with detail of geometry, section plane placed in the middle of the columns (4mm height of columns)

First optimization which can be seen in the Figure 2 was focused to increase of the heat transfer surface with low negative increase of pressure jump. Inspiration was found in the research on underwater natural heat transfer phenomena [KIM, 2017]. There was also a requirement to shape flow over the pylons to their bottoms with a higher temperature. CFD simulation shows a better heat transfer and a minimal change of the pressure jump, as can be seen in the simulation section. This design certainly requires a metal 3D print, but there were still issues [JOHNSON, 2021]. The size of the pylons and feature thicknesses were too small (<0.5mm) and the tilted faces above the pylons were also unprintable.

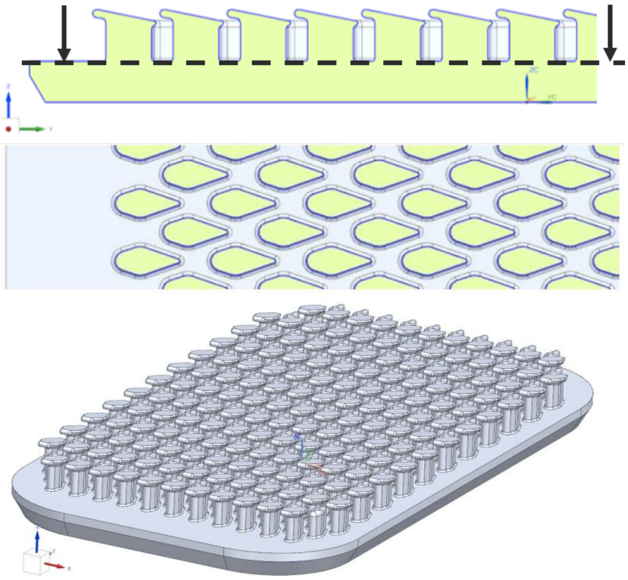

Figure 2. The 1st design iteration of cooling body, horizontal plane section is placed under overset faces

Many issues have to be solved in order to print technology. The FDM technology of metal, copper printing method was considered. Unfortunately, this technology was not able to print these small features in the model. The overset faces were unfortunately unprintable. Similar restrictions were observed for the DMLS technology [OCHSA, 2021]. Manufacturing requirements and restrictions induce design evolution as can be seen in Figure 3. Features were scaled up in general, and tilted faces were optimised for printing without support construction. The pylons are shaped like a tree concerning the distribution of heat flow. The structure can mix upper layer above the pylons into the lower bottom level. Average height of pylons is around 5.0 mm and minimal thickness is around 0.4mm.

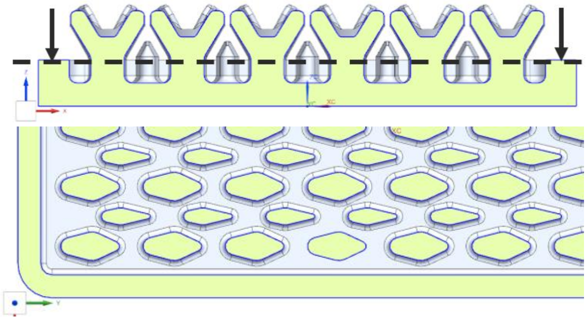

Figure 3. The second design iteration of the cooling body, plane section situated in the middle of the high of cooling shapes (bellow V-shape)

4 CFD SOLUTION

Simulation of fluid flow and heat transfer was performed by StarCCM+ solver. Generated mesh of the fluid region consists of polyhedral elements and a boundary layer. The solid region is discretized by tetrahedral elements. The boundary layer of the fluid region is characterized by three to four layers, stretched by factor 1.3. Detailed information can be seen in Table 1. The simulation was done for the required design for six sockets. Also, the measurement setup was simulated because of comparisons.

Design iteration	Fluid reg.	Solid region	Element size in fluid region
Initial (6ports)	1600000	3400000	2mm
1st (6ports)	18000000	9900000	1mm
2nd (2ports)	800000	1800000	2mm
Machined (2ports)	2600000	2800000	1.2mm

Table 1. **Mesh properties – number of elements and size**

SOLVER SETUP

Solver support the Final volume computation method. The turbulent model k-ω (SST) was chosen for the solution and computation was solved for residuals below 0.001(unitless). The convergence of steady state solution was good enough and all steady-state computations needed less than 300 iterations. The solver was set up with the all Y+ wall treatment approach. Temperature resistivity between heating elements and cooler was set to be 1600W*m^{-2}*K^{-1}, based on used thermal paste. PTFE plate between heating feature an aluminium cover defines heat transfer 100W*m^{-2}*K^{-1} concerning used 1.0 mm thick sheet. Heat source was setup on the contact face and cooling water source was define by the mass flow definition.

CFD RESULTS

The first series of CFD calculations was performed with original design of cooling case. This case is suitable for six cooled SiC elements. Every single SiC is loaded by 900W of waste heat in real conditions. Comparison in Table 2 shows lower temperature maximum and better homogeneity of temperature field on the transfer surface. The second series of CFD calculations was performed on the virtual model's measurement setup. It was done because of comparison with measurement data. The measurement setup is suitable for two cooled ports, but only one port is settled with heated elements, and another one is filled with polymer panel. All simulations were performed in steady-state regime. A comparison of results can also be seen in Table 2. Enlarge of the fluid flow surface can be identified; it is consistent with temperature decrease.

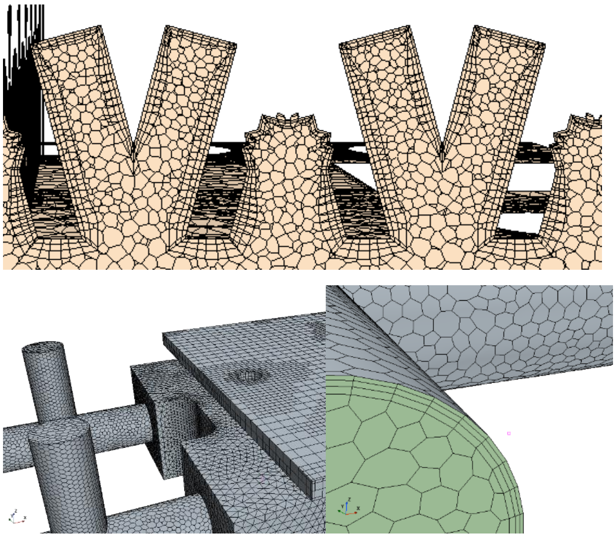

Figure 4 **Upper detail shows a mesh of the fluid regions of measured setup, also shows boundary layers in the cooling channels. Mesh details are performed by polyhedral mesh method by Star CCM+.**

Variant	Heat transfer surface	Trans-ferred heat power	Average Heat transfer coefficient	Maximal surface solid tempera-ture
Initial	10100 mm^2	6x900 W	1500 $W*m^{-2}*K^{-1}$	89.0°C
1st	12250 mm^2	6x900 W	1300 $W*m^{-2}*K^{-1}$	72.0°C
2nd	7200 mm^2	6x900 W	2200 $W*m^{-2}*K^{-1}$	70.1°C

Table 2. **CFD results for initial design 1st and 2nd design iteration**

5 PROTOTYPE – 3D PRINT

Prototype of cooling part was manufactured by Direct Metal Laser Sintering (DMLS) method. Detail pictures can be seen in Figure 6. Surface is relative good, with texture, details are precise and there are no vital defects. Specific details of printed methods are not available [DUDA, 2016]. Material of printed part is called EOS Aluminium Al2139 AM, defined by producer of additive technology.

The prototype case for laboratory measurement was manufactured by multi-jet fusion, powder additive technology. The printed material is polyamide PA12 with glass fibres. Material is suitable for the measurement. The case is tight, with no leakage. There can also be printed G1/8" threads which help with hydraulic connections. There is no prediction of high temperature, but the material should be able to withstand temperature above 100°C [MAREK, 2021].

Figure 5 **Printed prototype, made of aluminum, 1mm pattern underlay**

6 MEASUREMENT

Measurement was set up for one heated port. The surface was heated by four pieces of SiC. The size of SiC is 9.8mm x 24.8mm. It is heated by 250W each. Diconex 39-6572–250W high-temperature strip-line resistors on BeO substrate with NiCr thin resistive film and CuBe plating for perfect thermal transition. The assembly consists of four serial/parallel connected features with a total impedance of 50Ω and maximal performance of 1000W. The PTFE sheet was used to isolate SiC and aluminium cover plate. The thickness was 1mm. The thermal-transfer paste was used to decrease the thermal resistivity between SiC and the cooled exchanger. The resistivity of paste is 0.675 $W*m^{-1}*K^{-1}$. Electric performance was provided by regulated transformation Diametral RA1F250.100. The output voltage can be 5-250V. The maximal current is 10A. Measurements were done for different heating regimes: 200, 400, 600, and 800W. Measuring control unit QuantumX MX 1609, with sampling 10Hz was used. The placement of thermocouples type K can be seen in Figure 6. Pressure drop was identified by differential water level measurement with 1mm resolution. The mass flow was stated by volume flow measurement of control amount of liquid 1.5l/17s.

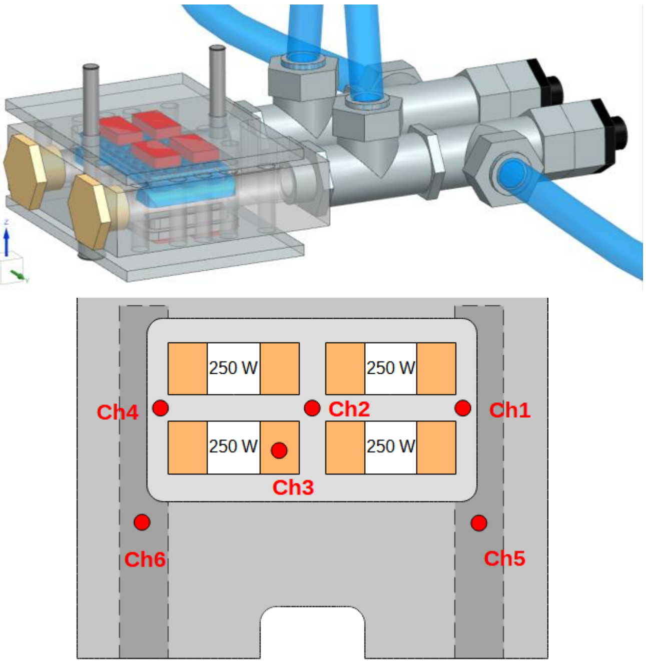

Figure 6 Measurement setup, heating and measuring positions

MEASUREMENT RESULTS

A few temperatures were measured. Six thermocouples were logged, and pressure drop was observed. Figure 7 and 8 shows two measurements for 200W and 400W of heat load. Obtained data show low temperatures of cooler and cooling liquid. All temperatures were below 22.0°C. Measured values for the 800W of heat loads can be seen in Figure 10. There was reached almost steady state conditions. Critical temperature of the surface of the SiC components was kept under 120.0°C, maximal measured temperature was around 115.0°C (Figure 10 – grey curve). Other temperatures were lower, under 30.0°C. The temperature of the printed case did not rise over 20.0°C.

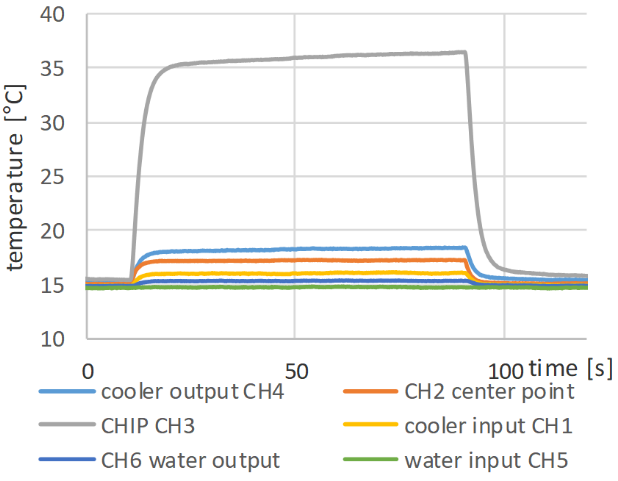

Figure 7 Measurement 200W; 5.3l/min

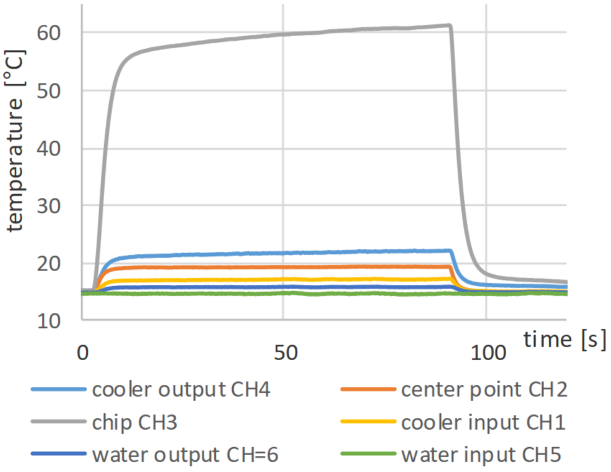

Figure 8 Measurement 400W; 5.3l/min

The pressure drop was measured by the parallel tube loop, which shows the pressure difference of the water column. All loading states were measured with the same mass flow – 0.088kg/s. This indicates the same pressure drop 3700Pa. The presumed precision of measurement is stated to be ±100Pa with respect to measurement assembly.

Variant	**Input water**	**Output water**	**Center point**	**Pressure drop**
Simulation (2ports)	15.0°C	17.0°C	23.0°C	4100Pa
Measurement (2ports)	14.8°C	16.9°C	23.7°C	3700Pa

Table 3. CFD results

Measured and simulated temperatures are comparable with good accuracy. Simulated temperature fields for 800W of heat load can be seen in Figure 9. Inlet part temperature is around 21.0°C, middle 23.0°C; outlet part is approximately 28.0°C, this agrees with measurement. Temperatures of cooling liquid are similar to simulation – input 15.0°C, output 17.0°C.

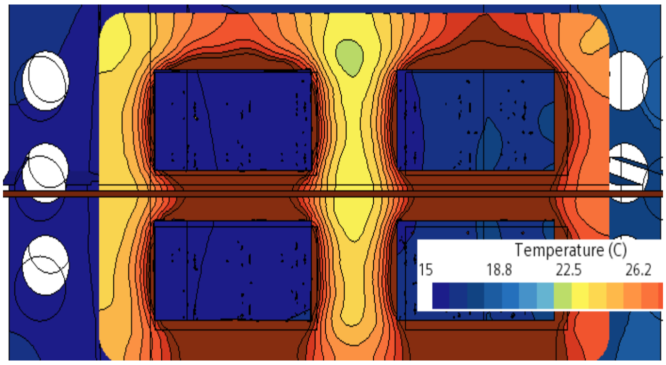

Figure 9 Simulation 800W, the average temperature on cooled surface 27.5°C

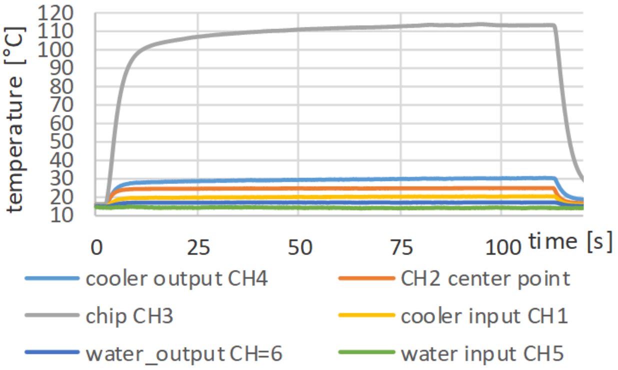

Figure 10 Measurement 800W; 5.3l/min

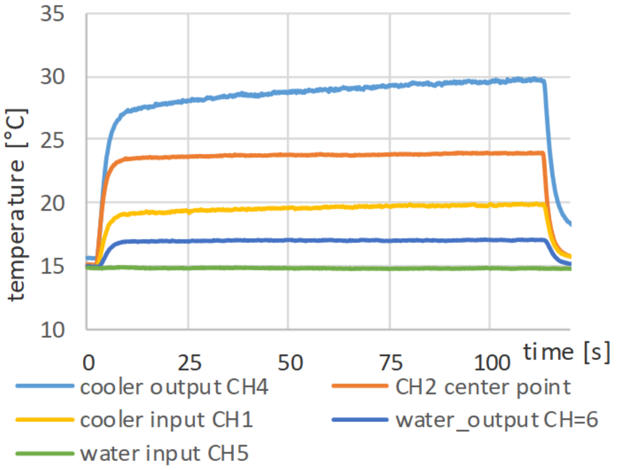

Figure 11 Measurement 800W; 5.3l/min – focused on lower temperatures

7 CONCLUSION

Complex research in the field of coolers was performed and provided simulations and measurements of a new type of cooling features. The initial design of the cooler was optimized to reach higher cooling performance, and homogeneous temperature field on the cooling surface. Simulated steady-state temperature peaks were decreased from 89°C to 70°C. Measurement verified accuracy of predictions with deviation below 15%. Empiric based shape of the cooling channel was optimized in two stages. Present high-tech methods like metal 3D print can provide specific shaped parts with specific properties. Additive methods in combination with optimization provide results with enormous potential in flow dynamics. Printed parts are still many times more expensive than machined parts (4times higher costs for presented specimens). Technology of additive manufacturing also specify crucial requirements. Serial production requires size of details and wall thickness >0.4mm for example. The next research will also consider milled version, inspired by optimized versions. There would be measured prototype, similar to previous research. Following research should provide cost-effective, high-performance cooling features for specific electronic parts.

ACKNOWLEDGEMENT

This research has been realized using the support of Technological Agency, Czech Republic, programme National Competence Centres, project # TN01000026 Josef Bozek National Center of Competence for Surface Vehicles. This support is gratefully acknowledged.

REFERENCES

[BERGMAN, 2011] Bergman T.L. a F.P. INCROPERA, 2011. Fundamentals of Heat and Mass Transfer. Hoboken: John Wiley & sons

[DINH 2018] DINH, Toan, Hoang-Phuong PHAN, Navid KASHANINEJAD a Tuan-Khoa NGUYEN, 2018. An On-Chip SiC MEMS Device with Integrated Heating, Sensing, and Microfluidic Cooling Systems. Advanced materials interfaces. 2018 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. Available from: doi: 10.1002/admi.201800764

[DUDA, 2016] DUDA, Thomas a L. RAGVAHAN, 2016. 3D Metal Printing Technology. In: International Federation of Automatic Control. s. 103-110. Available from: doi.org/10.1016/j.ifacol.2016.11.111

[GOH, 2017] GOH, Aik a Kim OOI, 2017. Scale-inspired enhanced microscale heat transfer in macro geometry. s. 142-152. Available from: doi: dx.doi.org/10.1016/j.ijheatmasstransfer.2017.05.067

[HUANG, 2017] HUANG, Zhiwei, Yunho HWANG a Reinhard RADERMACHER, 2017. Review of nature-inspired heat exchanger. s. 1-17. Available from: doi: 10.1016/j.ijrefrig.2017.03.006

[JOHNSON, 2021] JOHNSON, Malcolm, Santhush THILAKARATNE a Shivashish ARORA, 2021. How to Design a Heat Sink for Additive Manufacturing. Siemens Blogs

[KIM, 2017] KIM, Hyo a Hyun YOON, 2017. Forced convection heat transfer from the biomimetic cylinder inspired by a harbor seal vibrissa. Available from: doi: 10.1016/j.ijheatmasstransfer.2017.10.053

[MAREK, 2017] MAREK, V. a Z., HAJICEK, 2017. Thermal simulations based on macro-models. Mostar: Annals of DAAAM and Proceedings of the International DAAAM Symposium, s. 627–634

[MAREK, 2016] MAREK, Vaclav, 2016. Basic research of thermal transfer simulations [online]. Issue 1. Mostar: 27th DAAAM International Symposium on Intelligent Manufacturing and Automation, s. 578-585 [cit. 2016]

[MAREK, 2021] MAREK, Vaclav, MMS 2021, ed., 2021. Optimization and fast prototyping of polymer parts exposed to cyclic loading. IOP Conf. Series: Materials Science and Engineering. Available from: doi: 10.1088/1757-899X/1199/1/012013

[OCHSA, 2021] OCHSA, Dennis, Kira WEHNERTA, Jurgen HARTMANNA, Andreas SCHIFFLERA a Jan SCHMITT, 2021. Sustainable Aspects of a Metal Printing Process Chain with Laser Powder Bed Fusion (LPBF). s. 613-618. Available from: doi: 10.1016/j.procir.2021.01.163

[ROHM, 2020] ROHM CO., 2020. SiC Power Devices and Modules Application Note Rev.003. ROHM Co., Ltd.

[RUPP, 2019] RUPP, Ariana a Petra GRUBER, 2019. Biomimetic Groundwork for Thermal Exchange. MDPI, s. 1-23. Available from: doi: 10.3390/biomimetics4040075

CONTACTS:

Vaclav Marek, Ph.D.
University of West Bohemia, Regional technological Institute
Univerzitni 8, 30100 Pilsen, Czech Republic
+420721936147, marekv06@rti.zcu.cz