International Journal of Modern Manufacturing Technologies
ISSN 2067–3604, Vol. XIV, No. 3 / 2022
https://doi.org/ 10.54684/ijmmt.2022.14.3.92

HEAT TRANSFER OPTIMIZATION OF AN ELECTRONIC CONTROL UNIT IMMERSED IN NATURAL CONVECTION COOLANT

Cristina Georgiana Lates[1], Cristina Mihaela Dragan[2], Catalin Gabriel Dumitras[1]

[1]"Gheorghe Asachi Technical University of Iasi, Faculty of Mechanical Engineering and Industrial Management
Blvd. Mangeron, No. 59A, 700050, Iasi, Romania
[2] University Politehnica Timisoara, Faculty of Mechanics, Blvd. Mihai Viteazu, no.1, 300222, Timisoara, Romania
[3] Continental Automotive Romania SRL, Romania

Corresponding author: Cristina Georgiana Lates, latescristina@gmail.com

Abstract: The current paper aims to present a thermal dissipation optimization for an Electronic Control Unit (ECU) cooled with thermal paste. The improvement consists of replacing the inside air of the module with four single-phase dielectric coolants in natural convection and one silicone elastomer compound, each of which has a higher thermal conductivity than air. Two distinct experiments were performed: electronics immersed in coolant with and without thermal paste, exposed to an ambient temperature of between -40°C and 105°C. Temperature measurements on the hot spots of these solutions were compared to electronic modules that are cooled only with thermal paste.
Key words: thermal conductivity, convection, thermal paste, thermophysical properties of coolants.

1. INTRODUCTION

Cooling of electronic components in the automotive industry has started to be limited because of the large amount of power used to achieve functions. New requirements and the latest technologies have created a lot of opportunities and possibilities to develop new applications and functions for cars that users can connect with. Machine manufacturers must provide these features and services to compete in the market and meet customer demands. To accomplish this, from a business perspective, electronic units must become more powerful, smaller, and less expensive. This affects the thermal behaviour of the electronic control units.
Currently, in conventional cars, the heat transfer systems used are too conservative, the most common being thermal paste, metal housings, or fan cooling solutions. The advantages of those methods are that they are cheap and can still provide enough heat transfer for the power used. The metal casing for electronic products serves as a heat sink for the environment. Certain areas of the case are specially designed for cooling purposes, either on the component or directly on the Printed Circuit Boards (PCB) where the thermal paste is placed, to improve the heat transfer. Aside from the previously mentioned areas, distance restrictions to electronic components should be considered when designing the housings. There are circumstances when it is no longer possible to design cooling domes in the housing, where thermal paste can be applied, but the temperature on certain components must be kept below the manufacturer's maximum temperature. These factors, combined with the design constraints of housing manufacturing, result in numerous air-filled areas within the module. Because air is an insulating medium, it has no effect on the heat transfer of electronic components. Liquids are generally excellent conductors of heat because of their relatively higher thermal conductivity than air. Also, compared with solid thermal paste, a liquid takes the shape of the entire space between electronic components and the housing, and this will help in dissipating heat. Unfortunately, while water is one of the best heat transfer fluids, it has one major drawback when it comes to cooling electronics: it is very conductive of electricity. A good alternative is dielectric liquids. Immersion cooling, which uses dielectric fluids, has become one of the most promising ways to get rid of heat from high power densities.
Two types of direct immersion cooling exist: single phase immersion cooling (SLIC) and two-phase immersion cooling (2PIC). The challenges of 2PIC consist of being operationally complex and very costly and could not be implemented in this experiment. But the SLIC solution is more promising. Several studies have shown the benefits of using single-phase fluids. GRC Electrosafe, a hydrocarbon-based fluid, was highlighted [1] to have far superior heat transfer than an air-cooled solution. Mineral oil has achieved the best thermal results compared with silicone oil, synthetic and natural esters [2]. Mineral oil is also a strong option for battery immersion cooling systems because of their low cost, toxicity, and wide operating temperature range [3]. For electric vehicle batteries, many studies use hydrofluoroether [4,5] or natural and

synthetic esters [6] to investigate additional thermal solutions. Data centres use SLIC technology, and to achieve better thermal management, liquids are recirculated. A study with perfluorocarbon structured refrigerant (Fluorinert) proved that it can be a suitable coolant for immersion cooling with natural convection in a data center, [7]. As single-phase immersion coolants, Novec 3283, Novec 43, 50 cSt silicone oil, 20 cSt silicone oil, and soybean oil were compared. They found that the 20 cSt silicone oil works better in natural convection than the 50 cSt silicone oil because it has a lower viscosity.

Immersion of electronic components in viscous coolants provides a slight mechanical advantage due to the fluid's tendency to support electronic components. Depending on the viscosity of the fluid, it may also help stop vibrations and shocks by acting as a damper, [8].

This work proposes an improvement in heat transfer for automotive electronic modules exposed to an ambient temperature of between -40°C and 105°C, by replacing inside air with single-phase coolants without a pump or additional fan. Temperature measurements on the hot spots of these solutions were compared to an electronic module with only thermal paste cooling solution.

2. EXPERIMENTAL VALIDATION

2.1 Electronic module description

The electronic module used in the experiments is made up of a PCB that is placed in an aluminium housing and covered by a steel upper housing, as shown in Figure 1. The module tested has a total power of 50W. Figure 2 depicts the placement of all five temperature-measuring components: PCB, microcontroller (µC), two buck converters integrated circuit (ICs) and a two-phase DC-to-DC boost converter IC with serial peripheral interface (SPI) with thermal sensor embedded, which allows monitoring the junction temperatures.

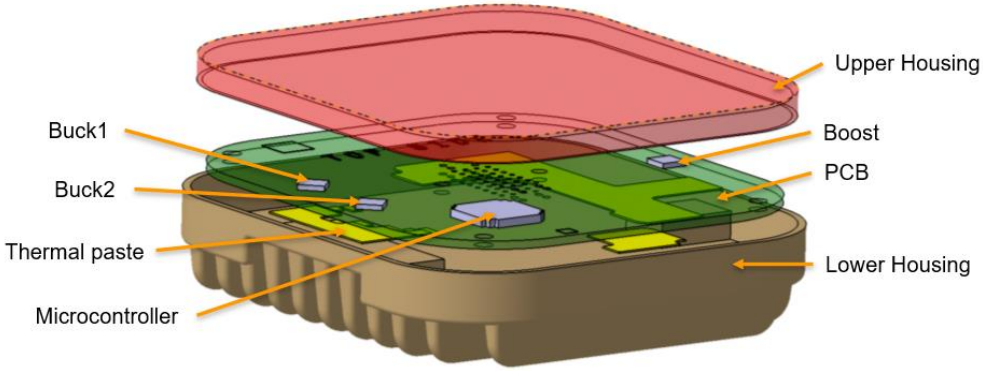


Fig. 1. Electronic module exploded view

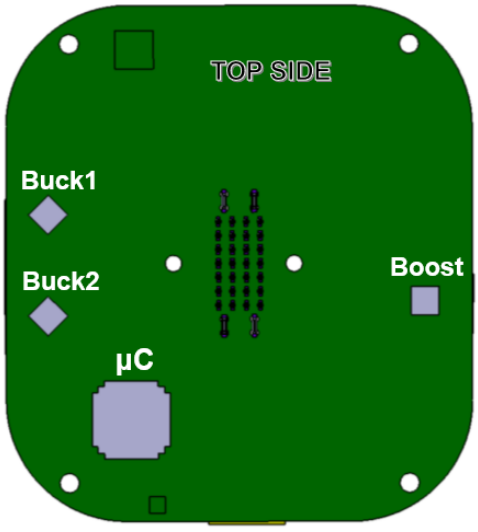


Fig. 2. Electronic components on top side PCB

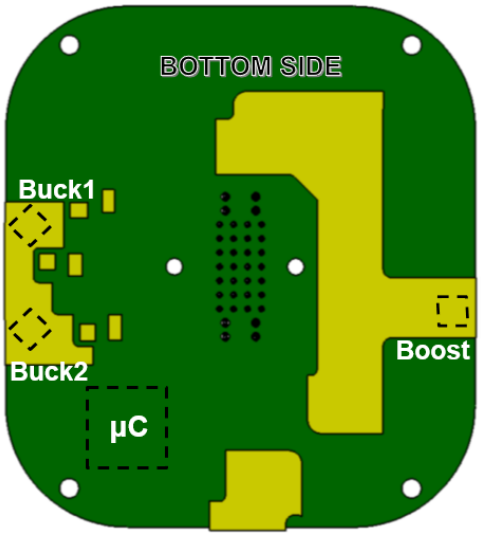


Fig. 3. Thermal paste dispensing on bottom side PCB

2.2. Test setup

During the measurements, eleven different modules were tested:

- one with thermal paste only, which was considered the reference for the complete study;
- one with thermal paste and silicone gel;
- four with thermal paste and different four coolants;
- one with silicone gel only;
- four with the same four different coolants only.

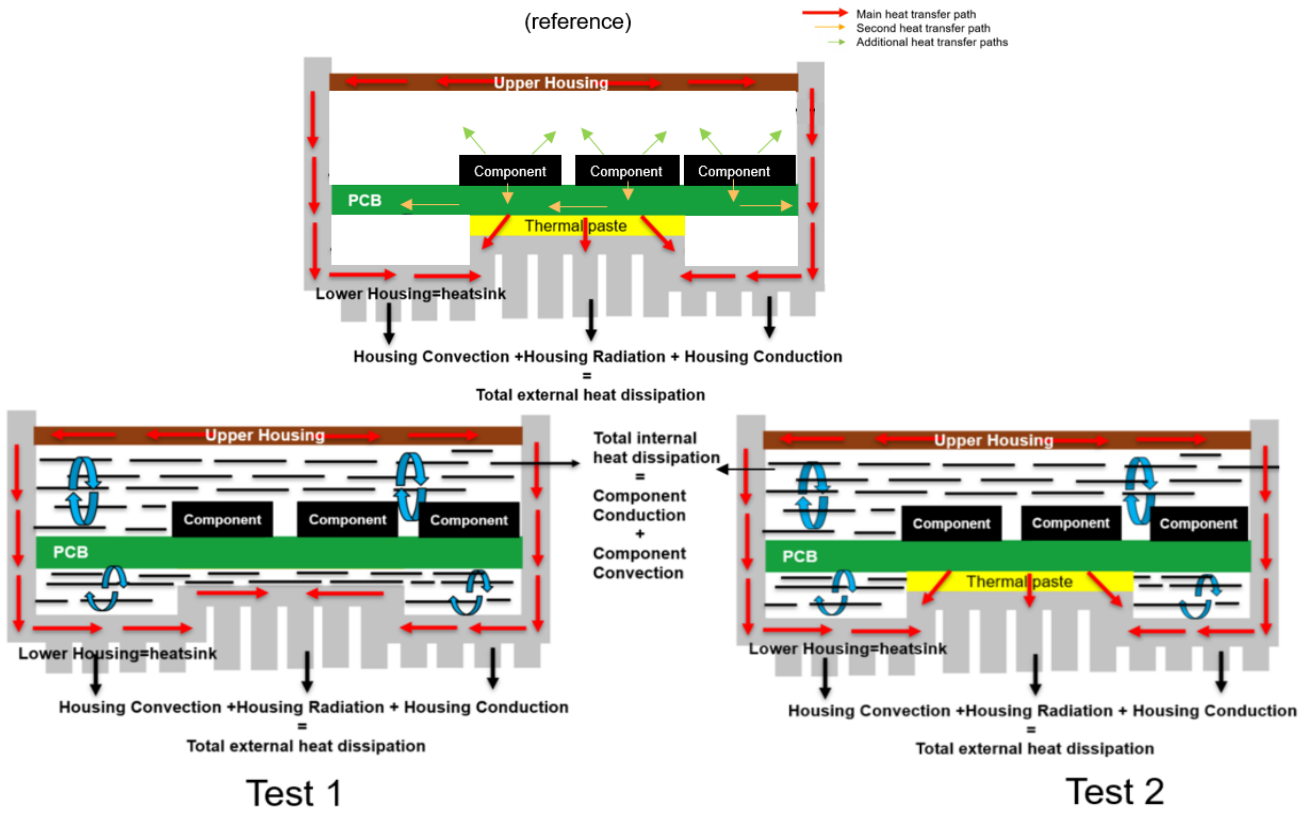


Fig. 4. Heat transfer schematic of experiments

Two experiments were conducted to determine the heat dissipation improvement, divided into Test 1 and Test 2. As shown in Figure 4, the first experiment consisted of five modules with coolants only, whereas the second experiment consisted of modules with coolants and thermal paste. The heat dissipation performance of both types of experiments was compared with the reference module. The reference module has Thermal Interface Material (TIM) under the PCB, where components Buck1, Buck2 and Boost were positioned as shown in Figure 3. The compound that is between the PCB and the heatsink is there to bridge the air gap, which would otherwise keep heat from moving efficiently.

The reference module is cooled only by thermal paste, which is the most commonly used cooling solution in electronic components. In this reference measurement, the main heat transfer path from the hot spot to the housing is via thermal paste only. In test 1, the main heat transfer path from the hot spot to the housing is via thermal paste, and the second transfer path is via free convection and molecular conduction of the fluid. In test 2, the main heat transfer path from the hot spot to the housing is via dielectric coolant only. When the surrounding fluid is a liquid, radiation from the heat-producing components is non-existent.

The thermophysical properties of the coolants chosen are listed in Table 1. The silicone gel is an encapsulating material, which is mainly used to improve the dielectric strength of the power module and to protect power devices from chemical contamination, moisture diffusion, and mechanical damage. The four different dielectric coolants used for this study are: hydrofluoroether (HFE), synthetic hydrocarbon (SHC) and two synthetic esters (one with Low Kinematic Viscosity (LKV) and the other with High Kinematic Viscosity (HKV).

Table 1. Thermophysical properties of coolants used

	Thermal conductivity[a]	Kinematic Viscosity[a]	Heat capacity	Density[a]	Specific heat	Coefficient of expansion[a]	Boiling point	Pour point
	[W/m*K]	[mm^2/s]	[J/K*m^3]	[kg/m^3]	[J/kg*K]	[1/K]	[°C]	[°C]
HFE	0.065	0.77	1838640	1630	1128	0.0013	129	-100
SHC	0.136	8.11[b]	1659000	790	2100	0.00067	>300	-57
HKV	0.147	75	1841136	968	1902	0.00075	high	-75
LKV	0.129	16.4	1746812	916	1907	0.00080	high	-75
Silicone gel	0.2	-		970	-	0.0003	-	-
TIM	2							

[a] at 20°C
[b] at 40°C

The modules were tested according to a method called temperature cycling. The test simulates varying low and high temperatures during the electrical operation of the system. The modules were placed into the climatic chamber, as shown in Figure 5. The temperature profile, as is illustrated in Figure 6, starts the program at room temperature for 30 minutes. Then the ambient temperature was gradually increased to 85°C in 2°C increments. The ambient temperature of 85°C was maintained for 70 minutes to ensure that the internal temperature of the components was stabilized. Then the ambient temperature was increased to 105°C (T_{max}) and maintained for 70 minutes. Following the stabilization period, the temperature was gradually reduced to -40°C (T_{min}) and held for 120 minutes before being returned to room temperature. The module operated in full power mode, which means around 50 watts of power in all the ambient temperature values described above. These temperature settings were selected because they cover a relatively large testing range for electronics in the automotive industry.

Fig. 5. ECUs placed in thermal chamber

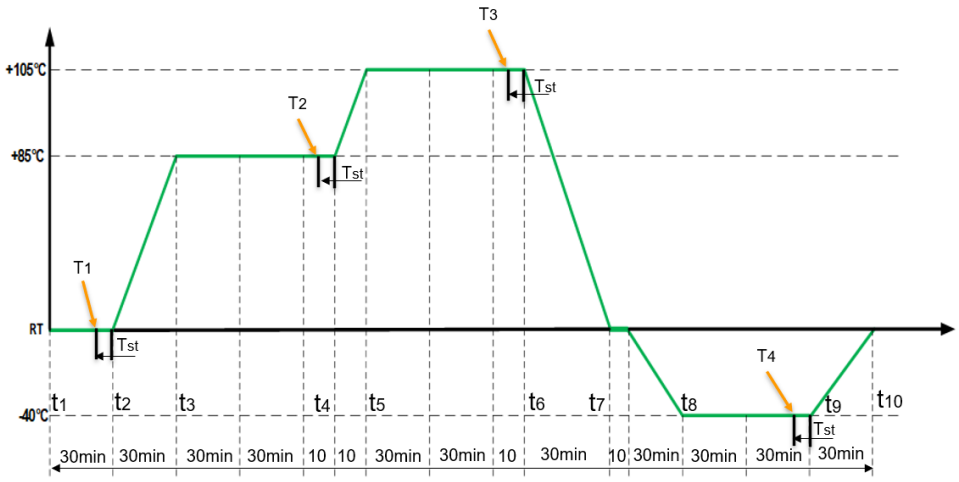


Fig. 6. Temperature profile

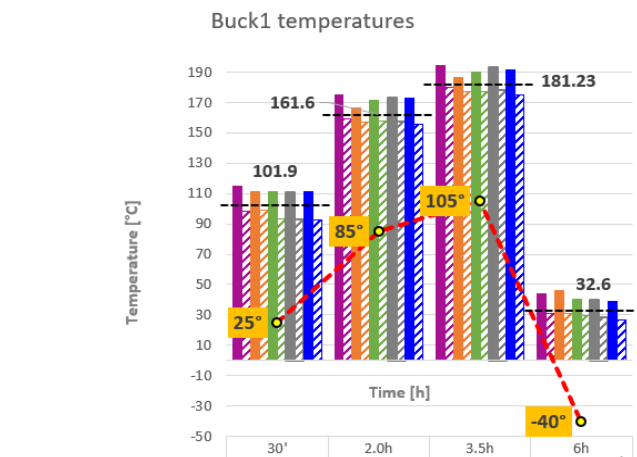
3. EXPERIMENTAL RESULTS

3.1 Temperature measurements

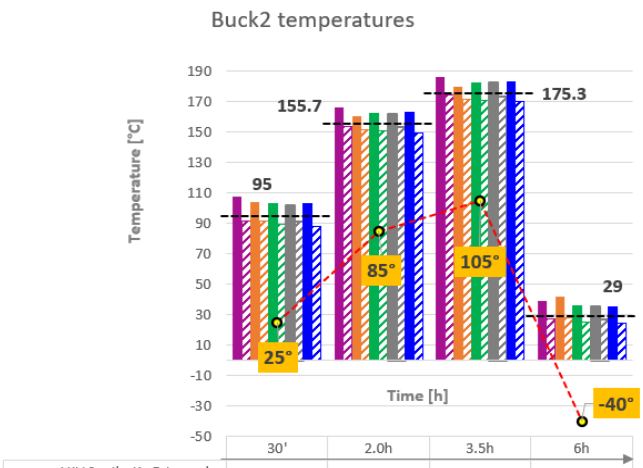
Temperatures were monitored in real time during the temperature profile steps. However, to simplify this evaluation, a single temperature at time tst (stabilization temperature time) was considered for each ambient temperature value, T1, T2, T3 and T4, depicted in Figure 6. The tst was set to 2 minutes before any change in profile temperature, and it was used to make sure that the temperatures measured across the whole system were stable at each temperature interval. Figure 7, Figure 8 and Figure 9 show the temperatures reached during the tests. The test results are divided into two categories in the graphs: solid bars represent the modules that were only filled with coolants, and pattern bars illustrate the modules that were filled with coolants and thermal paste.

The highest temperatures are achieved in modules that are filled with liquids only. The following graphics, Figure 10, Figure 12, Figure 14, show the temperature drop of each cooling solution tested, but this might lead to wrong conclusions.

Because there are eleven distinct modules utilized in each test, the amount of power consumed by each one could be different.

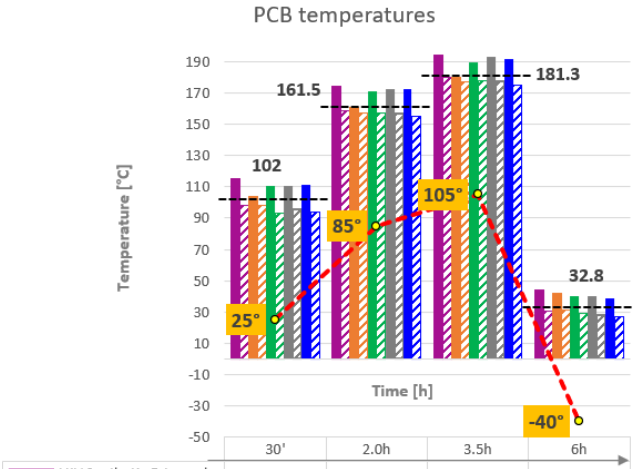


	30'	2.0h	3.5h	6h
LKV Synthetic Ester only	115	175	194.2	44
LKV Synthetic Ester_TIM	98.3	159.2	179.8	30.8
HFE only	111	166	186	46
HFE_TIM	99	157	177.1	31
SHC only	111.2	171	190	40
SHC_TIM	93	157.2	177	29.3
Silicone gel only	111.07	173	193	40
Silicone gel_TIM	93	157	177.6	28.3
HKV Synthetic Ester only	111.3	172.5	191	39
HKV Synthetic Ester_TIM	92.8	155.3	175	27
TIM only	101.9	161.6	181.23	32.6
Chamber temperature	25°	85°	105°	-40°

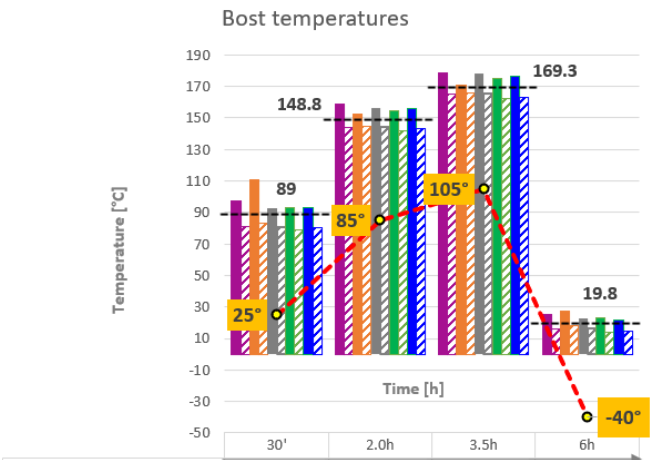


	30'	2.0h	3.5h	6h
LKV Synthetic Ester only	107.2	166	186	38.7
LKV Synthetic Ester_TIM	91.2	153.9	174	27.3
HFE only	104.1	160.6	179.8	41.6
HFE_TIM	91.5	151.6	171.7	28
SHC only	103	162	182	35.7
SHC_TIM	89.1	150.7	171	25
Silicone gel only	102	162	182.8	35.6
Silicone gel_TIM	91	153.2	173	27
HKV Synthetic Ester only	103.2	163	183	35
HKV Synthetic Ester_TIM	88.1	149.1	169.9	24
TIM only	95	155.7	175.3	29
Chamber temperature	25°	85°	105°	-40°

Fig. 7. Temperature values on Buck 1 and Buck 2.



	30'	2.0h	3.5h	6h
LKV Synthetic Ester only	115.5	174.6	194.5	44
LKV Synthetic Ester_TIM	98	159	180	30.6
HFE only	104.1	160.6	179.8	41.6
HFE_TIM	98	157.3	177	31
SHC only	111	171.2	190	40
SHC_TIM	93	157.4	177.8	29.1
Silicone gel only	111	173	193.5	40
Silicone gel_TIM	95.4	157	177.4	28.3
HKV Synthetic Ester only	111.3	172.6	191.7	39
HKV Synthetic Ester_TIM	93.6	155.1	175	27
TIM only	102	161.5	181.3	32.8
Chamber temperature	25°	85°	105°	-40°



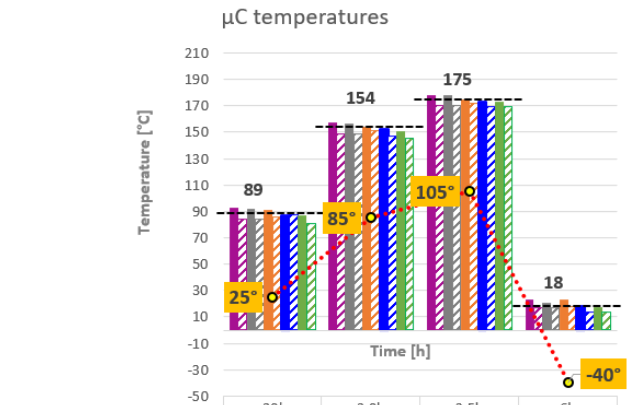
	30'	2.0h	3.5h	6h
LKV Synthetic Ester only	97	158.8	178.6	25
LKV Synthetic Ester_TIM	81.2	144.2	165.2	16.2
HFE only	111	152.5	171	27.5
HFE_TIM	83.5	145	165.7	18
Silicone gel only	93	156.6	178	23
Silicone gel_TIM	81	144.2	165.4	16.1
SHC only	93	154.4	175	23
SHC_TIM	79	142	162	13.8
HKV Synthetic Ester only	93	155.7	176.8	22
HKV Synthetic Ester_TIM	80.3	143	163.2	14.9
TIM only	89	148.8	169.3	19.8
Chamber temperature	25°	85°	105°	-40°

Fig. 8. Temperature values on Boost and PCB

Therefore, to avoid being dependent on this power's slight fluctuations, as well as the overall temperature of the surrounding environment, the thermal resistance should be considered. The thermal resistance was calculated with formula (1). The thermal resistance shows how a thermal cooling solution is increasing the temperature per watt.

$$R_{th} = \frac{\Delta T}{P} \quad (1)$$

In the following graphics analysis, the temperature differences of the modules with coolant only and of the modules with coolant and thermal paste relative to the modules with thermal paste only were performed.



	30'	2.0h	3.5h	6h
LKV Synthetic Ester only	92.9	157	178	23
LKV Synthetic Ester_TIM	84	149	170	17
Silicone gel only	92	156.8	178	21
Silicone gel_TIM	84	149	170	17
HFE only	91.3	154.2	175	23
HFE_TIM	86.1	151	172	18
HKV Synthetic Ester only	87	152	173.2	18
HKV Synthetic Ester_TIM	87	147	169.2	14
SHC only	87	151	173	17.7
SHC_TIM	81	145	169	14
TIM only	89	154	175	18
Chamber temperature	25°	85°	105°	-40°

Fig. 9. Temperature values on µC

Because the thermal behavior is similar at all analyzed ambient temperature values, in the current paper it highlights only the worst-case conditions, 105°C ambient temperature.

The thermal improvement [%] relative to the standard used solution, where the modules are only with thermal paste, was calculated based on the thermal resistances. A minus improvement shows better thermal behavior and a plus improvement shows worse thermal behavior compared with the thermal paste only solution.

For thermal cooling solutions with liquid and TIM, it was observed that the best fluid for Buck 1 was HKV liquid, which was explained by the highest thermal conductivity.

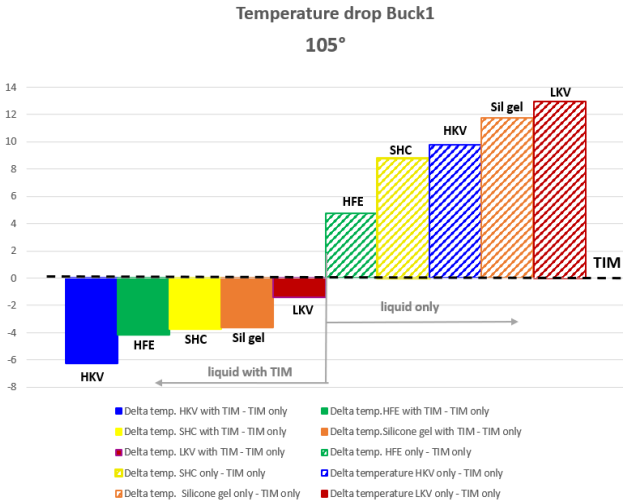


Fig. 10. Temperature difference between coolant only, coolant liquids with TIM and TIM only on Buck 1

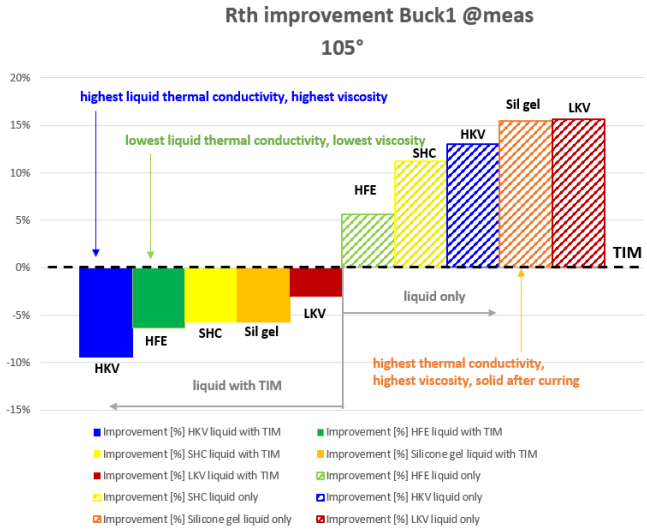


Fig. 11. Thermal resistances improvement between coolant only, coolant with TIM and TIM only on Buck 1

The average improvement in HKV coolant with thermal paste compared to thermal paste only is approximately 6°C and 17°C compared to liquids alone. The second parameter that was observed to count is the kinematic viscosity, which if it is lower, it is better due to easier and optimal contact between components and housing. A low kinematic viscosity value decreases the possibility of having air trapped at contact surfaces. Because of this, HFE liquid demonstrates a second better thermal performance compared to other liquids that have been tested. Also, silicone gel has the highest value of thermal conductivity, but because of its high kinematic viscosity, there is a high possibility of having air trapped during curing at contact between components and housings.

For thermal cooling solutions with liquid only, without any thermal paste, all the solutions are worse than the reference cooling solution with thermal paste only. The best thermal behavior is for HFE coolant, which has the lowest kinematic viscosity. Also, except for LKV coolant, which has unexplained thermal behavior during the measurements, silicone gel with the highest kinematic viscosity has the worst thermal behavior. So, the kinematic viscosity of the coolant seems to be more important than its thermal conductivity.

The thermal behavior of µC wa slightly different than the other components. The µC is the only component that has no thermal paste underneath, and it is also affected by other components' power consumption, because Boost and Buck converters are controlled with PWM (Pulse Width Modulation) signals generated by a microcontroller. Due to the thermal runaway effect on µC, power consumption increases with the temperatures and decreases if the cooling solution is better. This fact explains why modules filled with HFE or HKV only registered temperatures that were 2°C or 3°C lower than when thermal paste was used alone.

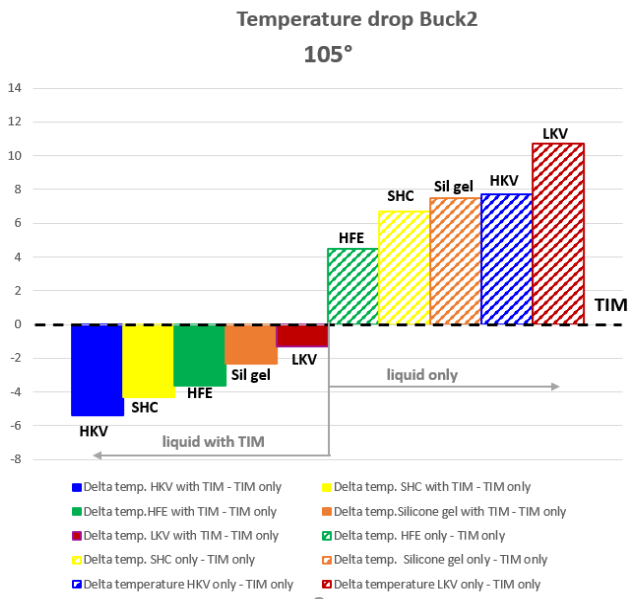


Fig. 12. Temperature difference between coolant only, coolant liquids with TIM and TIM only on Buck 2

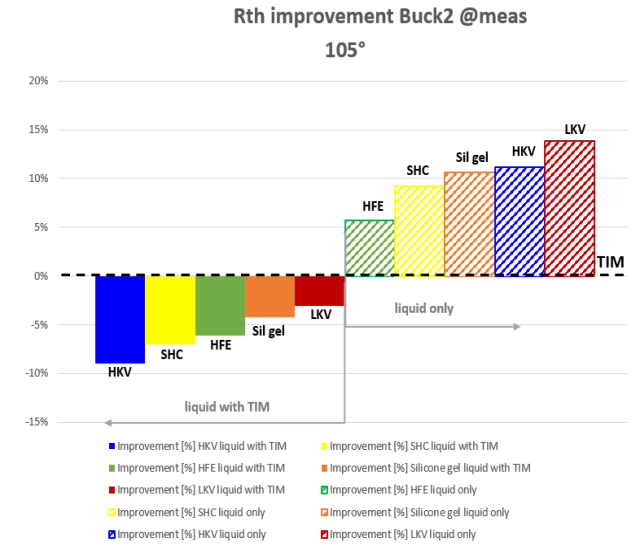


Fig. 13. Thermal resistances improvement between coolant only, coolant with TIM and TIM only, on Buck 2

4. CONCLUSION

Comparing the different coolants, it is obvious that HKV-Synthetic Ester is the best coolant. In second and third place among the alternative liquids were SHC-synthetic hydrocarbon and HFE-hydrofluoroether, while in fourth place was silicone gel. The synthetic ester LKV performed the worst in these tests.

In modules containing only coolants, the thermal behavior of the coolants remained in the same sequence for each analyzed component. HFE-hydrofluoroether demonstrated the greatest performance, followed by SHC-synthetic hydrocarbon and HKV-hydrofluoroether. Silicone gel and LKV failed to provide the optimal results. However, the strategy that utilizes solely cooling fluids moving by natural convection yields worse results compared to thermal paste.

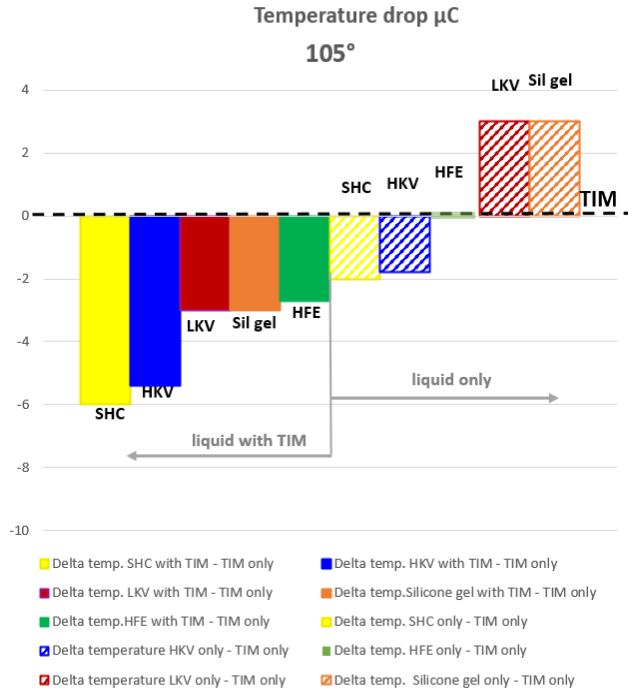


Fig. 14. Temperature difference between coolant only, coolant liquids with TIM and TIM only on µC

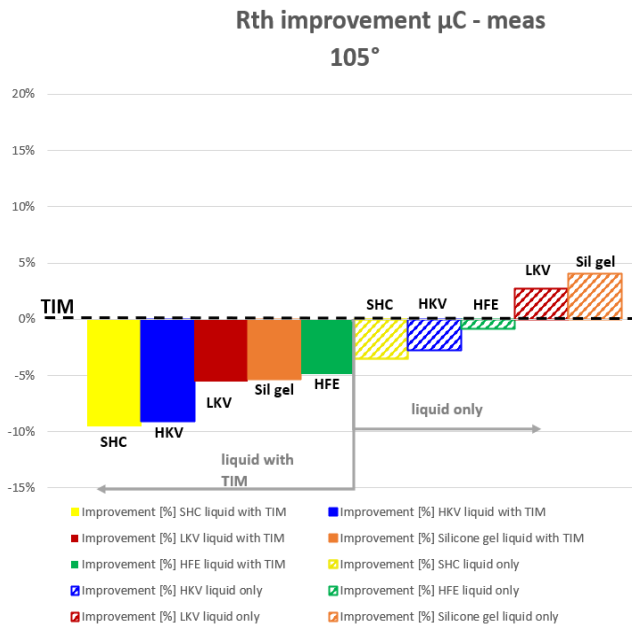


Fig. 15. Thermal resistances improvement between coolant only, coolant with TIM and TIM only on µC

By looking at modules with liquid and thermal paste, it was found that the thermal performance of liquids with high thermal conductivity is better. When only liquid cooling solutions were used to cool down electronic parts, the coolants with the lowest viscosity showed the lowest temperature increase compared with thermal paste only.

These measurement results demonstrate that thermal paste cooling solutions could be enhanced by replacing the volume of air within the rest of the electronic modules with coolant. Depending on the chosen fluid, the improvement was up to 10% for the used boundary

conditions.

The fundamental advantage of single-phase liquid imerssion cooling with natural convection over other cooling methods such as fans, heat pipes, Peltier, etc. is that the ECU requires no additional space. An extremely important and necessary measure is the hermetical sealing of the ECU. Also, the expansion of the coolant should be considered.

5. REFERENCES

1. Varma, D., (2020). *GR Cooling, Cold wars-part 2 Data center two-phase versus single-phase immersion cooling GR Cooling*. Available from: https://www.grcooling.com/wp-content/uploads/2020/03/grc-blog-library-tech-comparison-%E2%80%94-two-vs-single-phase-immersion-cooling.pdf
Accesed: 12.01.2022
2. Lecuna R., Delgado F., Ortiz A., Castro P. B., Fernandez I., Renedo C., (2015). *Thermal-fluid characterization of alternative liquids of power transformers: a numerical approach,* IEEE Trans. Dielectr. Electr. Insul., 22, 2522-29.
3. Shah, J.M., Eiland, R., Siddarth, A., Agonafe, D., (2016). 15th InterSoc. Conf. Therm. Thermomechanical Phenom. Electron. Syst. ITHERM, 316-25.
4. Mayer, T., Donzow, E., (2019). *Design of battery packs: strategies for high energy density and range*, ATZelectronics Worldw., 14, 26-31.
5. Wang, Y.F., Wu. J.T., (2020). *Thermal performance predictions for an HFE-7000 direct flow boiling cooled battery thermal management system for electric vehicles*, Energy Convers. Manag., 207(1), 112569.
6. Lashbrook, M., Al-Amin, H., Martin, R., (2017). *Natural ester and synthetic ester fluids, applications and maintenance*, 10th Jordan Int. Electr. Electron. Eng. Conf. (JIEEEC), 17208713.
7. Matsuoka, M., Matsuda, K., Kubo, H., (2017). *Liquid immersion cooling technology with natural convection in data center*, IEEE 6th Intern. Conf. on Cloud Net., IEEE, 17281396.
8. Bureau of ships navy department, (1955). *Guide Manual of Cooling Methods for Electronic Equipment*, Washington 25 DC.

Received: July 23, 2022 / Accepted: December 15, 2022 / Paper available online: December 20, 2022

© International Journal of Modern Manufacturing Technologies