BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Volumul 71 (75), Numărul 3, 2025
Secţia
CONSTRUCŢII DE MAŞINI
DOI: 10.2478/bipcm-2025-0028

OPTIMIZATION OF PARAMETRIZED HEAT FINS DESIGN BASED ON THERMAL SIMULATION

BY

ANDREEA ISTRATE* and OANA DODUN

“Gheorghe Asachi” Technical University of Iași,
Faculty of Machine Manufacturing and Industrial Management, Iași, Romania

Received: June 10, 2025
Accepted for publication: August 13, 2025

Abstract. Heat fins are used to improve thermal solutions in Electronic Control Units (ECU) as being the most common and cost-effective way to enable heat transfer and protect electronics side of the unit. Heat fins have limitations, including material, manufacturability, fins position, and available area size. Research was done to reveal existing solutions and their usability. Existing literature presents solutions with good effect in heat transfer, but this paper introduces solutions designed to be easily manufactured and cost-effective. Most of the solutions proposed by the literature with high thermal improvement are mostly fitting on prototypes. The case study proposed in the paper consists in a parametrized heat fins configurable design. The different solutions are introduced in a thermal simulation to highlight the efficiency of the heat transfer. Fins number and shape prove to be the most critical factors in heat transfer. However, thickness and shape are essential, as they affect the distance between fins and air flow.

Keywords: Heat fins; heat transfer; cooling; Electronic Control Unit; thermal.

*Corresponding author; *e-mail*: andreea.cretu@student.tuiasi.ro
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1. Introduction

Heat transfer is an important factor that influences the proper functioning of electronic systems as the overheating can affect the electronic components and therefore the system will be compromised (Ali *et al*., 2025). 55% of electronic systems are failing due to overheating (Shahid *et al*., 2025). Through heat transfer, cooling of electronic components can be achieved.

Heat transfer is achieved either through natural convection or through forced convection. Natural convection occurs when there is no induced motion to the air, only based on natural air flow. Forced convection is achieved with help of some mechanical device such like fans (Ting, 2022). Depending on the heat flux, natural or forced convection might be chosen, keeping in mind that forced convection will imply additional components and cost.

Fins (or extended surfaces) are solid geometries created to increase convection by increasing the surface area, thereby improving heat transfer (Bhavik and Megha, 2019). Copper behaves better in heat transfer than aluminum, but being cheaper, lighter and corrosion resistant, the aluminum is widely used in electronic systems enclosures together with heat fins.

Fins can be designed in a variety of forms in an attempt to improve the heat transfer. (Bhavik and Megha, 2019) simulated circular, square and rectangular fins and found the rectangular ones to be more effective. Indeed, the rectangular (straight) shape provided a larger surface for convection. (Keshavan *et al*., 2023) studied the behaviour for three different forms of fins: trapezoidal, trapezoidal with Y tips and trapezoidal wavy fins (vertical waves). Wavy fins showed more promising thermal behaviour, but none of these designs are actually proper for mass production, only good for prototypes. Madhavadas simulated different designs, including no fins, rectangular (straight) fins, circular fins, and rectangular fins with circular fins (more fins with smaller diameter). The straight fins achieved the best result (Madhavadas *et al*., 2021).

This paper focuses on creating a parametrized design of an Electronic Control Unit containing a top enclosure with heat fins that can be configured as per the needed application and can be fine-tuned easily after thermal simulation.

2. Parametrized Design of Heat Fins

The parametrized model in this case study is based on the Skeleton method in order to be able to modify needed parameters from the Skeleton part easily. The model is created in CATIA software, but this method can be used in other CAD software, such as Inventor, Creo, NX, and others.

The parameters included in Skeleton (Fig. 1) that are changeable are the component size, thickness, number of fins, fin form, fin height, fin thickness, and component material. The following simulations for fins include variations of fin parameters to understand which factors influence the thermal behaviour.

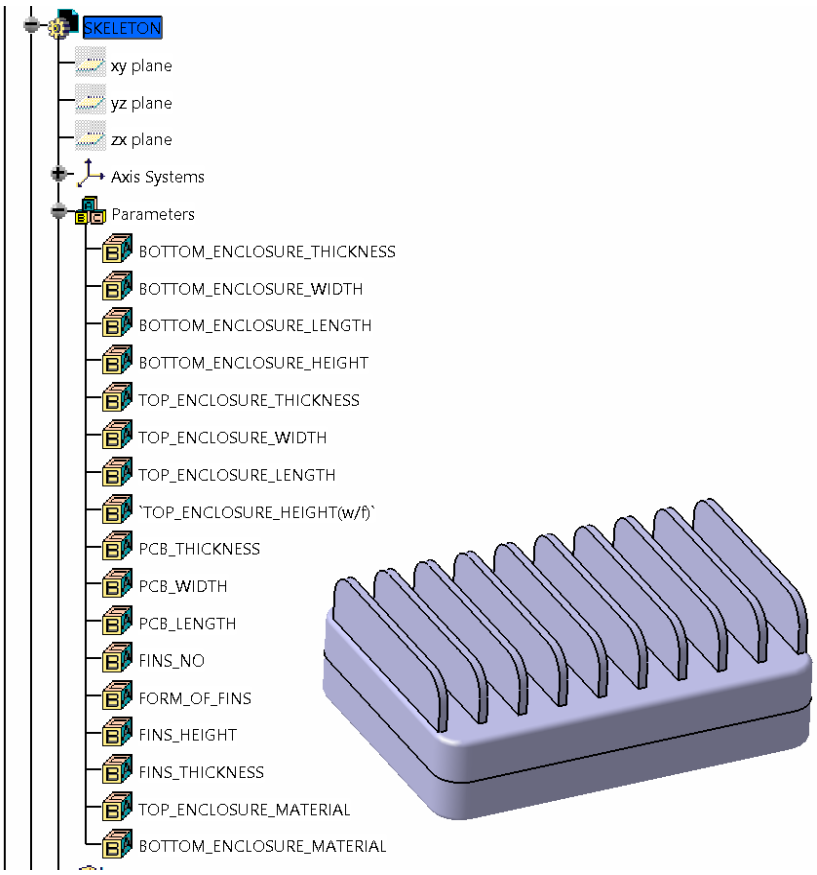


Fig. 1 – Skeleton parameters for the proposed heat fins.

Top enclosure rules are more of an interest as the fins are created on it. The component contains the fins form rule (Fig. 2) and the material rule (Fig. 3).

```
if `External Parameters\FORM_OF_FINS` =="STRAIGHT"
{PartBody\Assemble.2\Activity = true
PartBody\Assemble.4\Activity=false}
else if `External Parameters\FORM_OF_FINS` =="SHAPED"
{PartBody\Assemble.2\Activity = false
PartBody\Assemble.4\Activity=true}
```

Fig. 2 – Form of fins rule.

```
if `External Parameters\TOP_ENCLOSURE_MATERIAL` =="ALUMINUM"
{PartBody\Material ="Aluminium"}
else if `External Parameters\TOP_ENCLOSURE_MATERIAL` =="PLASTIC"
{PartBody\Material ="Plastic"}
else if `External Parameters\TOP_ENCLOSURE_MATERIAL` =="ZINC"
{PartBody\Material ="Zinc"}
else if `External Parameters\TOP_ENCLOSURE_MATERIAL` =="COPPER"
{PartBody\Material ="Copper"}
```

Fig. 3 – Materials rule.

All the parameters were linked between Skeleton and components sketches or rules in order to enhance the direct updates.

3. Thermal Simulation of Parametrized Design

Cases considered for thermal simulation are defined in Table 1. Two dimensions were used for fin thickness and height, and two types of fin shapes. One of the samples had a higher number of fins. All 20 cases were simulated on three different materials: aluminium alloy, copper alloy, and zinc.

Table 1

Simulation cases considered for aluminium alloy, copper alloy, and zinc

Case	Form	Fins orientation	Fins thickness [mm]	Fins no.	Fins height [mm]
Case 1	straight	vertical	1.5	10	10
Case 2	straight	vertical	1.5	10	15
Case 3	straight	vertical	2	10	10
Case 4	straight	vertical	2	10	15
Case 5	shaped	vertical	1.5	10	10
Case 6	shaped	vertical	2	10	10
Case 7	shaped	vertical	1.5	10	15
Case 8	shaped	vertical	2	10	15
Case 9	straight	vertical	1.5	13	10
Case 10	straight	vertical	1.5	13	15
Case 11	shaped	vertical	1.5	13	10
Case 12	shaped	vertical	1.5	13	15
Case 13	straight	vertical	1.5	15	10
Case 14	straight	vertical	1.5	15	15
Case 15	shaped	vertical	1.5	15	10
Case 16	shaped	vertical	1.5	15	15
Case 17	straight	horizontal	1.5	11	10
Case 18	straight	horizontal	1.5	11	15
Case 19	shaped	horizontal	1.5	11	10
Case 20	shaped	horizontal	1.5	11	15

Simulation parameters assumption:

– Mesh element size: 0.002 m

– Convection – film coefficient: for Aluminum Alloy – 17 W/m²·°C, for Copper Alloy – 14 W/m²·°C and for Zinc – 17 W/m²·°C (convection film coefficient named also heat transfer coefficient varies with temperature, fins design, size and spacing; the values for aluminum alloy are considered as an average value of measurements made by Khalifa; the value used for zinc alloy was assumed to be similar to aluminum alloy) (Khalifa and Almousawi, 2016)

– Ambient temperature: 25°C

– Applied temperature: 100°C. It was assumed to be the maximum temperature of the microcontroller, where the application area 20 x 20 mm (Fig. 3).

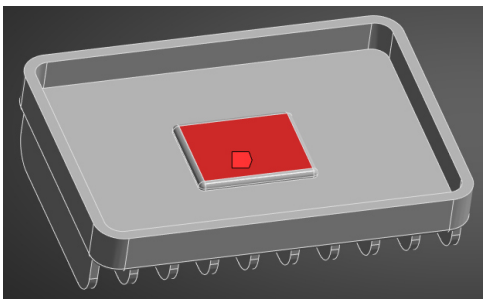


Fig. 3 – Temperature application area.

Obtained temperature and convection values can be seen in Table 2, Table 3 and Table 4.

Table 2

Obtained temperatures in ANSYS for Aluminum Alloy

Case no.	Min. Temperature [°C]	Avg. Temperature [°C]	Max. Heat Flux [W/m²]	Min. Heat Flux [W/m²]	Avg. Heat Flux [W/m²]
Case 1	91.108	94.899	$4.02 \cdot 10^5$	1105.9	33318
Case 2	88.948	93.753	$4.68 \cdot 10^5$	971.43	37407
Case 3	91.489	95.138	$3.15 \cdot 10^5$	649.66	32342
Case 4	89.499	94.071	$3.76 \cdot 10^5$	586.46	36124
Case 5	91.028	94.634	$3.39 \cdot 10^5$	323.26	23657
Case 6	88.783	93.238	$3.94 \cdot 10^5$	253.16	24310
Case 7	91.436	94.84	$3.72 \cdot 10^5$	763.93	22879
Case 8	89.369	93.605	$4.54 \cdot 10^5$	579.3	22644
Case 9	90.447	94.485	$3.52 \cdot 10^5$	1079,5	33189
Case10	87.972	93.139	$4.35 \cdot 10^5$	898.58	37780

Case 11	90.335	94.249	$4.15 \cdot 10^5$	533.54	23848
Case 12	87.759	92.661	$5.3 \cdot 10^5$	305.19	24721
Case 13	90.007	94.24	$4.25 \cdot 10^5$	1098.2	34020
Case 14	87.328	92.744	$5.34 \cdot 10^5$	1023.4	38786
Case 15	89.884	94	$3.95 \cdot 10^5$	475.82	24179
Case 16	87.104	92.282	$5.55 \cdot 10^5$	406.14	25001
Case 17	92.3	94.957	$4.45 \cdot 10^5$	860.45	32656
Case 18	90.312	93.719	$5.26 \cdot 10^5$	838.22	36684
Case 19	92.151	94.714	$4.6 \cdot 10^5$	1173.2	25180
Case 20	90.122	93.304	$5.8 \cdot 10^5$	851.36	26382

Table 3

Obtained temperatures in ANSYS for Copper Alloy

Case no.	Min. Temperature [°C]	Avg. Temperature [°C]	Max. Heat Flux [W/m²]	Min. Heat Flux [W/m²]	Avg. Heat Flux [W/m²]
Case 1	96.8	98.17	$3.5 \cdot 10^5$	979.41	29170
Case 2	95.964	97.73	$4.13 \cdot 10^5$	764.54	33205
Case 3	96.944	98.259	$2.73 \cdot 10^5$	562.53	28248
Case 4	96.178	97.852	$3.3 \cdot 10^5$	477.41	31959
Case 5	96.768	98.074	$2.95 \cdot 10^5$	274.13	20722
Case 6	95.898	97.542	$3.48 \cdot 10^5$	213.19	21595
Case 7	96.923	98.152	$3.23 \cdot 10^5$	652.85	20004
Case 8	96.127	97.682	$3.99 \cdot 10^5$	518.84	20057
Case 9	96.546	98.013	$3.08 \cdot 10^5$	988.25	29191
Case10	95.575	97.49	$3.86 \cdot 10^5$	782.73	33778
Case 11	96.502	97.927	$3.63 \cdot 10^5$	467.45	20986
Case 12	95.489	97.313	$4.7 \cdot 10^5$	280.89	22116
Case 13	96.375	97.919	$3.72 \cdot 10^5$	976.79	30018
Case 14	95.316	97.334	$4.75 \cdot 10^5$	926.8	34849
Case 15	96.327	97.831	$3.47 \cdot 10^5$	386.64	21344
Case 16	95.225	97.162	$4.95 \cdot 10^5$	377	22473
Case 17	97.249	98.201	$3.87 \cdot 10^5$	756.47	28435
Case 18	96.492	97.733	$4.62 \cdot 10^5$	763.95	32372
Case 19	97.193	98.114	$4 \cdot 10^5$	1027.8	21964
Case 20	96.419	97.582	$5.1 \cdot 10^5$	765.9	23327

Table 4

Obtained temperatures in ANSYS for Zinc

Case no.	Min. Temperature [°C]	Avg. Temperature [°C]	Max. Heat Flux [W/m²]	Min. Heat Flux [W/m²]	Avg. Heat Flux [W/m²]
Case 1	87.874	93.013	$3.89 \cdot 10^5$	1056.6	32092
Case 2	85.084	91.514	$4.5 \cdot 10^5$	952.87	35752
Case 3	88.373	93.331	$3.05 \cdot 10^5$	631.71	31194

Case 4	85.793	91.931	$3.61 \cdot 10^5$	591.71	34590
Case 5	87.772	92.651	$3.27 \cdot 10^5$	316.86	22776
Case 6	84.876	90.82	$3.79 \cdot 10^5$	249.57	23222
Case 7	88.305	92.923	$3.6 \cdot 10^5$	750.42	22049
Case 8	85.628	91.3	$4.37 \cdot 10^5$	550.23	21664
Case 9	87.016	92.468	$3.4 \cdot 10^5$	1009.6	31883
Case10	83.847	90.722	$4.16 \cdot 10^5$	865.07	35966
Case 11	86.872	92.147	$4 \cdot 10^5$	513.15	22900
Case 12	83.58	90.082	$5.07 \cdot 10^5$	286.05	23523
Case 13	86.447	92.148	$4.09 \cdot 10^5$	1009.3	32622
Case 14	83.038	90.216	$5.1 \cdot 10^5$	960.02	36825
Case 15	86.29	91.824	$3.81 \cdot 10^5$	456.91	23177
Case 16	82.759	89.6	$5.3 \cdot 10^5$	378.19	23729
Case 17	89.441	93.063	$4.31 \cdot 10^5$	826.48	31546
Case 18	86.844	91.431	$5.06 \cdot 10^5$	791.63	35167
Case 19	89.244	92.732	$4.46 \cdot 10^5$	1123.7	24294
Case 20	86.599	90.87	$5.57 \cdot 10^5$	786.94	25255

The initial expectation would be to think that increasing the fins' thickness will decrease temperature, but actually a slight increase in temperature can be observed in case 3 (2 mm) compared with case 1 (1.5 mm). Also, this different behaviour cannot be attributed to the convection surface size: as it can be observed in Table 3, the thicker fins correspond to slightly bigger convection surface. It is also important to consider that increasing the fins' thickness will decrease airflow efficiency.

Table 3

Cases and convection surfaces size in ascending order [mm²]

Case 1	***Case 3***	***Case 5***	***Case 7***	***Case 9***
17728.41	17804.61	18486.94	18562.562	20134.71
Case 11	***Case 13***	***Case 2***	***Case 4***	***Case 17***
21121.5	21738.92	21878.41	22004.61	22931.67
Case 6	***Case 15***	***Case 8***	***Case 19***	***Case 10***
23026.41	22877.88	23150.1	24259.41	25529.71
Case 12	***Case 14***	***Case 16***	***Case 18***	***Case 20***
27022.82	27963.92	29687.09	29696.67	31712.51

When analysing Fig. 4, it can be observed also that highest convection surface area does not necessarily come with better thermal behaviour, nor in the rest of the cases. Cases 16, 12, 14 and 10 (in this order) are behaving better in all materials. Cases 16 and 12 correspond to shaped fins form. The difference between them is the height and fins number of fins. Cases 14 and 10 correspond to the straight fins form and the same difference as in the previous pair of cases.

Seems that fins number and fins height have similar effects. Design of cases 16, 12, 14 and 10 can be observed in Fig. 5.

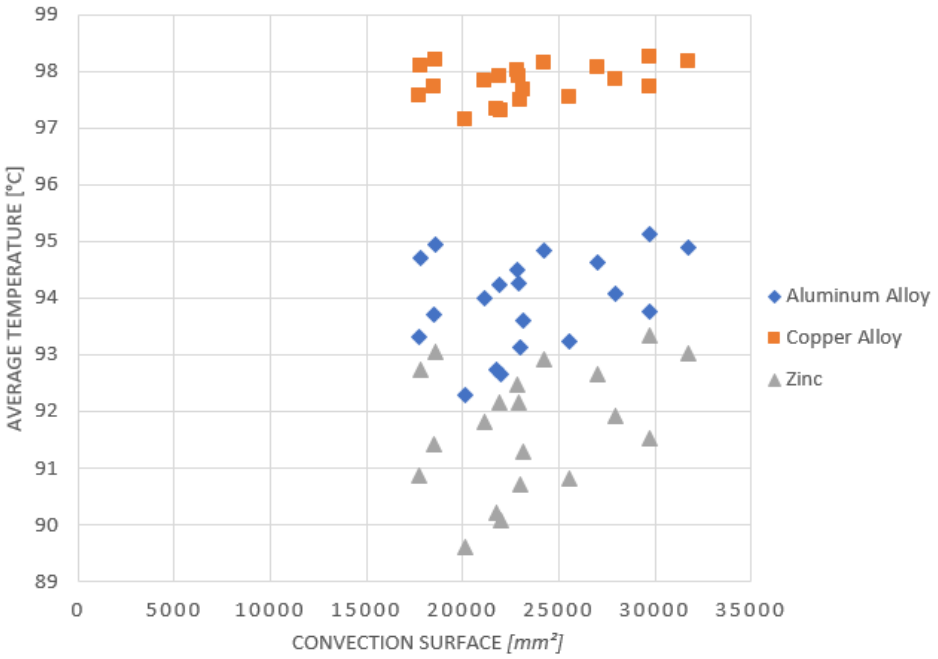


Fig. 4 – Evolution of temperature considering convection surface and material.

The given shape change of fins brings some improvement in heat transfer, but not that big as the increase in the height or fins number. Since this shaping of the fins is limited in width it cannot increase the convection surface that much as the height can. The only limitations in height and fins number case would be the manufacturing limits: as example, in casting, the height cannot increase too much as it could affect the material filling and fins number could affect distance between fins which corresponds to tool wall thickness.

Changing the fins orientation as in cases 17 to 20 does not come with any improvement, average temperature values obtained being all of them over 90°C (all three materials). However in real applications, fins orientation could have an important contribution because of the air flow direction. Design of case 17 can be observed in Fig. 6 (as an example for horizontal fins).

Materials choice is also an important factor in thermal management. They come with a contribution of several degrees from the start. Best material option considered in the study proved to be the zinc material; however, the difference to aluminum is only 2.2°C on average. The difference between zinc and copper alloy is 6.06°C, which makes copper alloy a bad option. Considering that aluminum alloy parts are lighter and easy to manufacture aluminum alloy is

a good option. Additionally, choosing from a variety of aluminum alloys options allows for a closer thermal behaviour to zinc alloy.

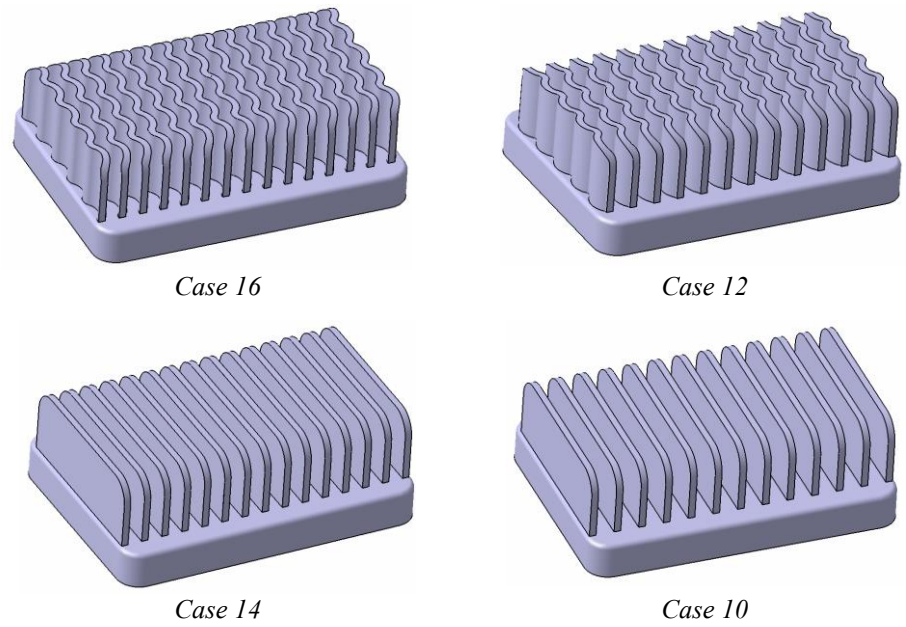


Fig. 5 – Best four designs with good thermal behaviour.

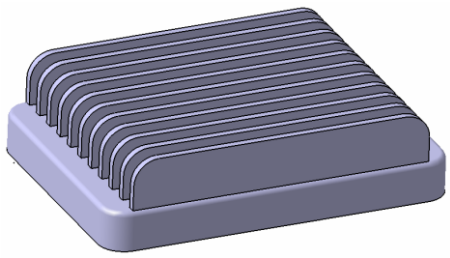


Fig. 6 – Horizontal orientation of fins.

4. Conclusions

The study results show that increasing fins thickness is not a good idea as it is not always improving heat transfer, coming also with reduced airflow and maybe also manufacturing limitations. In cases when small temperature differences matter, shaping of fins can be introduced instead of the straight fins. It must be considered that shaping width will be limited to not affect airflow.

The better and simplest change to improve heat transfer through fins remains the height and fins number increase within manufacturing limits together with good material choice.

Future work will focus on experimental validation of the numerical results, which should be carried out by manufacturing and testing prototypes under controlled laboratory conditions. The design space could also be systematically explored using the Taguchi method for experimental design, in order to identify the most influential parameters and their optimal levels with a reduced number of simulations or tests. Moreover, alternative fin geometries such as pin or perforated profiles could be investigated, aiming to enhance heat transfer without significantly increasing manufacturing complexity. Hybrid cooling approaches, combining passive fins with active methods such as forced convection or heat pipes, may also be explored for high-power ECU applications. The use of multi-objective optimization techniques could support the identification of fin configurations that achieve an optimal balance between thermal performance, weight, cost, and manufacturability. In addition, advanced materials, such as graphene-enhanced aluminum alloys or metal foams, should be considered for their potential to improve thermal dissipation further.

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OPTIMIZAREA PROIECTĂRII PARAMETRICE A NERVURILOR DE RĂCIRE UTILIZĂND SIMULĂRI TERMICE

(Rezumat)

Nervurile de răcire sunt utilizate pentru a îmbunătăți soluțiile termice în unitățile de control electronic, fiind cea mai comună și mai rentabilă modalitate de a permite transferul de căldură și de a proteja partea electronică a unității. Nervurile de răcire au limitări legate de material, productibilitate, poziționarea acestora și dimensiunea suprafeței disponibile. Au fost efectuate cercetări pentru a dezvălui soluțiile existente și posibilitatea utilizării lor. Literatura existentă prezintă o mulțime de soluții cu efect important în transferul de căldură, dar această lucrare are scopul de a introduce soluții concepute pentru a fi ușor de fabricat și rentabile. Majoritatea soluțiilor propuse de literatură care prezintă o îmbunătățire termică ridicată se potrivesc mai ales pentru prototipuri. Studiul de caz propus în lucrare constă într-un model configurabil și parametrizat al nervurilor de răcire. Diferitele soluții sunt introduse într-o simulare termică pentru a evidenția eficiența transferului de căldură. Numărul și forma nervurilor se dovedesc a fi cei mai importanți factori în transferul de căldura. Cu toate acestea, grosimea și forma nervurilor sunt importante, acestea afectând distanța dintre nervuri și fluxul de aer.