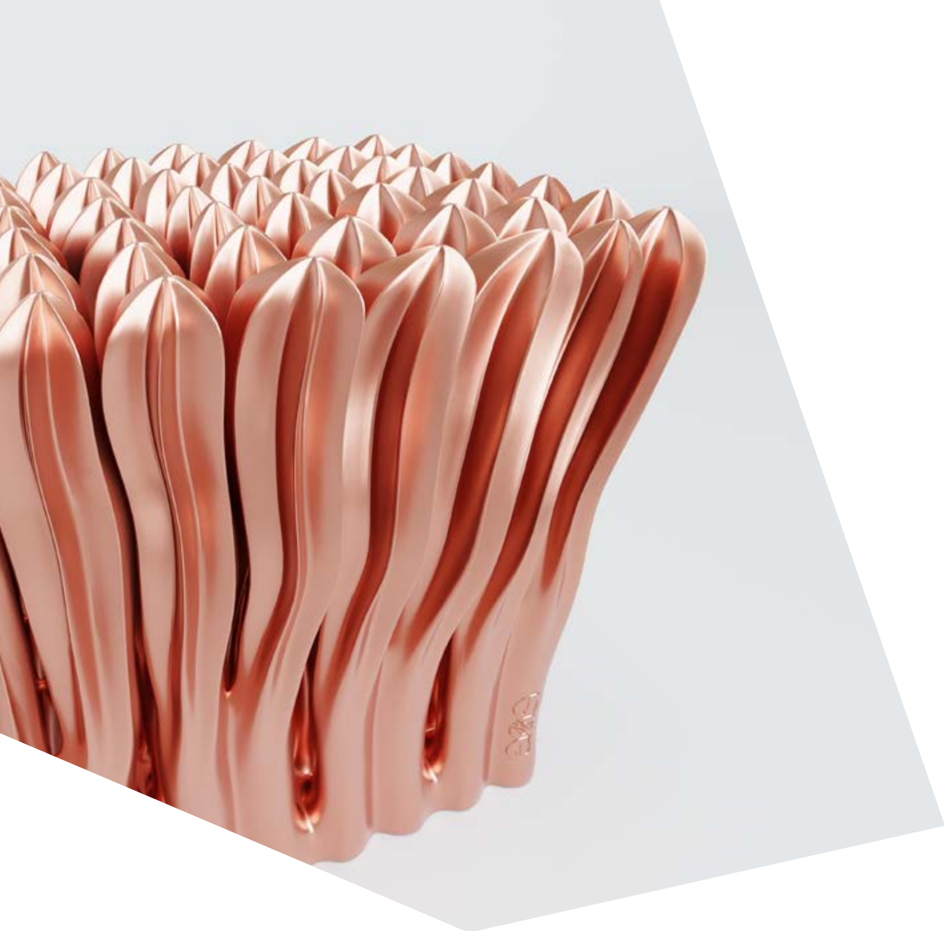

Whitepaper

This Whitepaper Gives Information About:

- How to achieve excellent thermal management with restricted space
- What becomes possible by applying additive manufacturing to CPU cooling
- Why additive manufacturing is key for the further miniaturization of electronic devices
- How new design freedom paves the way for radical innovations

A Disruptive Innovation of Thermal Management

By
Dr. Matthias Hoeh
Senior Business Development Manager
EOS GmbH

Reinventing a High-Performance CPU Cooler with Additive Manufacturing

High heat loads limit the miniaturization of portable computers, power electronic devices and high-power LED lighting. Most ambitious technological solutions from the lab are not ready for mass production and deployment in consumer products. But industrial 3D printing, or so-called additive manufacturing, can bridge the gap for thermal management components and keep lossy electronics cool even when the available space is severely limited. The freedom of design provided by 3D printed thermal management components offers the same or superior effectiveness as conventionally manufactured components, but requires much less space. Enlarged surfaces, any-shape geometries and conformal cooling channels are among the opportunities of this manufacturing technology.

The efficiency gains that can be achieved were demonstrated with a gaming CPU cooler design for additive manufacturing. To maintain the same chip temperature, the new part requires 81 % less space and 93 % less weight than the best-in-class conventional cooler.

THESYS Experts for Thermal Solutions

AM METALS

eos

Frontpage:
CPU cooler in biomimetic design
Designer: Moritz Heller

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The Future of Thermal Management for Electronics

Electronic components are developing in two basic directions: Performance is increasing and size is decreasing.

Everything revolves around one central problem: heat [1]. This is true at microscopic scales, e.g. where noise on a quantum level limits how small the structures of processing units can become [2,3]. But it also manifests at macroscopic scales, where the amount of heat that can be transported away from high-performing components limits the performance per volume.

Everything revolves around one central problem: heat!

As a fundamental consequence of non-ideal systems, losses and hence heat cannot be avoided. But they could be reduced in the future. Innovative technologies that perform tasks much more efficiently than before can circumvent the excess heat limitations. For example, high hopes have been placed in the transition from electronics to photonics. Even now, photons rather than electrons are the information carriers used by the backbones of modern communication [5]. In the future, photonics might also advance into microprocessors and improve the performance per volume of computers [6]. New algorithms for quantum simulators and one day possibly even quantum computers can solve certain classes of problems more efficiently than classical, purely binary computers [7].

But these approaches are all decades away from being deployed to consumer products. The question at hand is how to radically improve thermal solutions for existing electronic devices and push the boundaries of miniaturization. A solution would serve a huge market demand.

- → Laptops and mobile phones are becoming thinner and more powerful.
- → Communication infrastructure is a data bottleneck and needs to support ever higher transfer rates, while at the same time a landscape of bulky transmission towers must be avoided.
- → Electric cars are full of high power electronics that need to be integrated into a limited space.

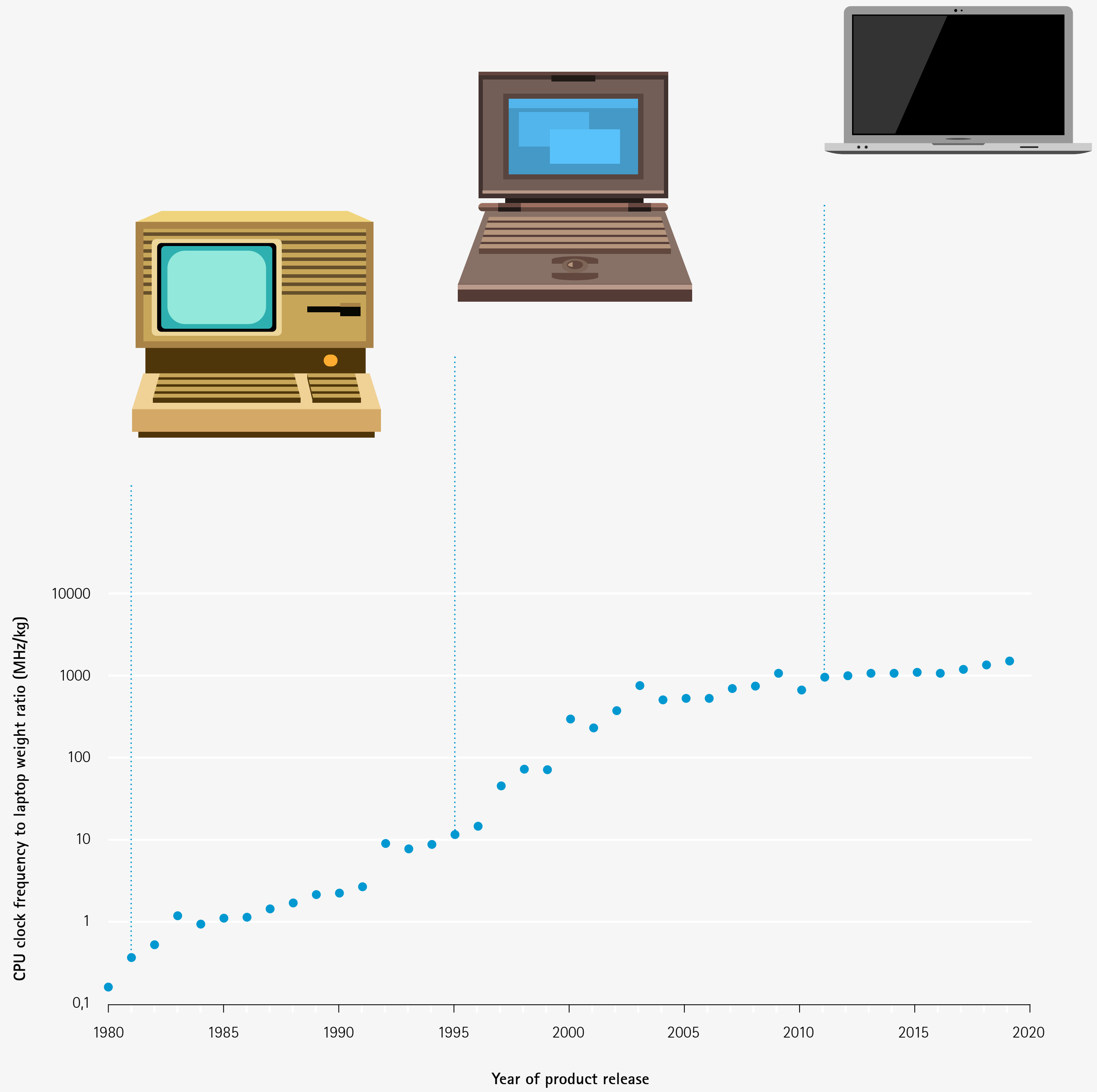
In each of these markets, new thermal solutions need to be developed. Significant technical progress is required within the next few years.

The Challenges of Miniaturization: Paper-Thin Laptops

To illustrate the miniaturization trend, the historical development of portable computers is a good example. Their steady increase in performance and decrease in size has been particularly challenging. Portable computers have come a long way since the 1980s. The miniaturization of sub-systems and components was a major aspect of their hardware development.

The CPU clock frequency is a readily available measure of performance, and there is plenty of historical data for computers. The clock frequency has been stagnating since about 2004; instead, the number of cores has been growing exponentially [8]. The stagnation of the clock frequency has several reasons, the most prominent being excess heat creation. Higher frequencies require higher voltages, but the excess heat associated with them cannot be fully compensated by cooling technology improvements. In a nutshell, the limitations in heat transfer restrict the maximum clock frequency and hence the single-thread performance of the processor*.

We analyzed the situation for laptops as an example of powerful computers with limited available space. To measure the technological advancement of miniaturization, we normalized the CPU clock frequency with respect to weight. The resulting historical analysis shows that miniaturization of laptops is slowing down. The data points in figure 1 are randomly picked laptop types with different display sizes from various manufacturers [10]. The chart shows how the exponential CPU clock frequency growth ended in around 2004.



Laptops are just one example, but they convincingly illustrate the importance of efficient cooling in small spaces and demonstrate how additively manufactured thermal management components can revitalize the miniaturization of electronic devices.

*Multi-thread performance can be increased by performing multiple core processing at lower clock frequencies for each core.

Figure 1: Historical development of the laptop
The trend of CPU clock frequency relative to weight shows that a limit has been reached for single-core processing.

Small and Light Weight Heat Exchangers Come at High Cost

For the study, we focused on CPU coolers directly mounted on the chip via a heat spreader.

If we look at the solutions available today, we notice two main types of CPU coolers. One is optimized for manufacturability, the other for performance. The most economical way to mass manufacture chip coolers is by extruding aluminum, but the performance of products manufactured by this technique is limited due to its design restraints (figure 2a).
For optimum cooling performance, complex assembly parts are required. These are composed of sub-components, for example milled components (figure 2b).

In a housing with extremely limited space for the heat exchanger, neither of the two commonly used types is a good choice. Further miniaturization of the best-performing coolers would be costly, because it involves further production steps and longer machining times. This represents a restraint on the further miniaturization of computers and other electronic devices.

The goal of this study was to break the miniaturization limit and innovate a CPU cooler that matches the best-in-class products while requiring much less space and material. By designing for additive manufacturing from the start, the typical restraints of conventional production methods were overcome.

Figure 2a: Simple air cooler made by extrusion
Retail price approx. 16 USD [9]

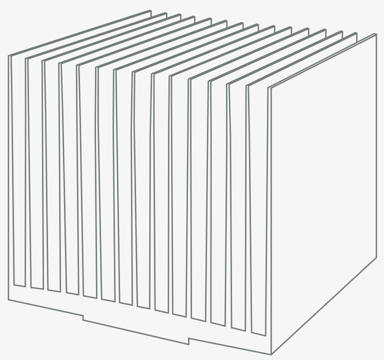
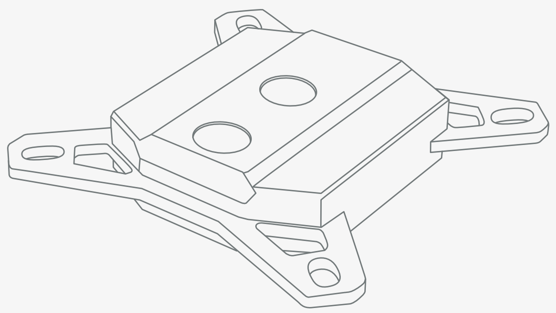


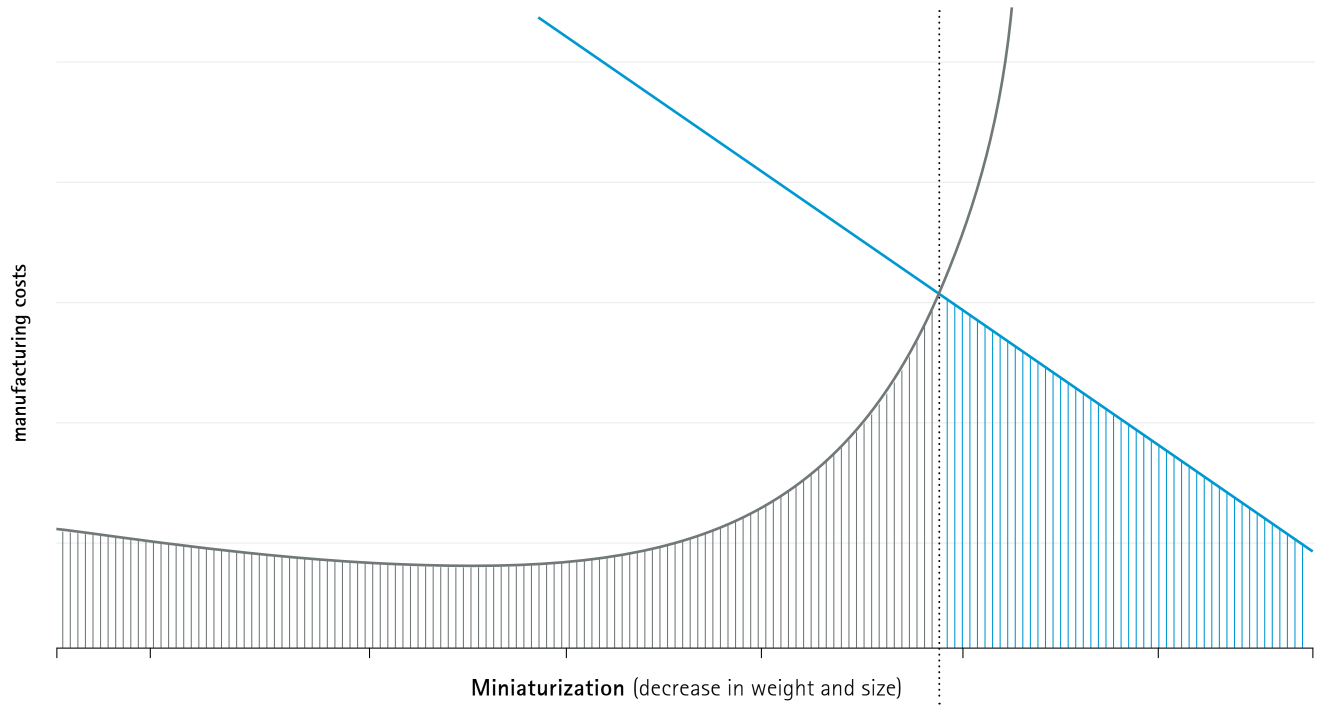
Figure 2b: Complex water cooler assembled from sub-components made by different conventional manufacturing techniques
Retail price 62 USD [9]



Additive Manufacturing Is Ideal for Miniaturized Heat Exchangers

The economics of complex parts made with additive manufacturing by laser sintering are exactly the opposite of the economics of subtractive manufacturing (i.e. most conventional manufacturing technologies). Roughly speaking, the less material the laser has to melt, the less machining time is required. Delicate and complex parts are therefore faster and cheaper to produce than massive and simple parts (figure 3).

Additive manufacturing thus opens a door to a new world of thermal management solutions. Old limitations are obsolete and new ideas can flourish. For thermal solutions, the rewards include increased surface areas, complex shaped internal channels for optimized coolant flow and functional integration. Miniaturization and increased heat transfer performance are the goals.



Subtractive manufacturing
is economically viable for bulky heat exchangers

Additive manufacturing
is more economically viable for miniaturized heat exchangers

Figure 3: Delicate and complex components are where additive manufacturing shines, whereas massive parts with simple geometries are better suited for traditional subtractive manufacturing methods.

Innovating a High-Performance Gaming CPU Cooler

The process of reinventing a CPU cooler was headed by AM Metals, a company specializing in application development for additive manufacturing. The starting point was the best-in-class CPU cooler currently on the market for gaming computers. It meets extreme heat transfer requirements to enable the common practice of overclocking.

As part of the project, new ideas for innovative cooling flow geometries were generated and the heat transfer path was optimized. As a final design result, the area directly above the bottom plate was equipped with an arrangement of specially designed pins. The pin arrangement was adapted to the specific thermal footprint of the CPU.

The goal was to reduce its size and weight while maintaining best-in-class cooling performance.

Figure 4a: Cross section of benchmark CPU cooler, optimized for conventional manufacturing

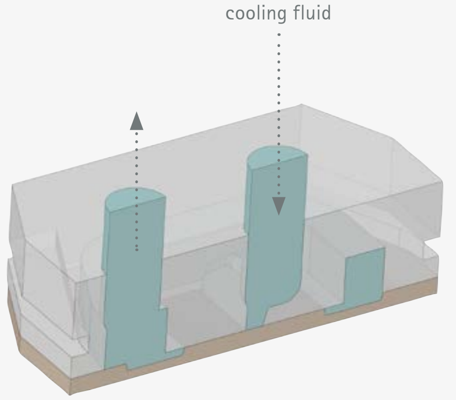
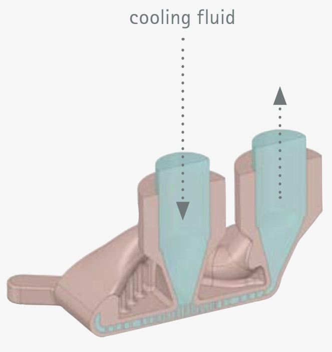


Figure 4b: Cross section of 3D printed CPU cooler



Comparison with Best-In-Class CPU Cooler

To predict and compare the performance of the 3D printed CPU cooler to the benchmark CPU cooler, a highly accurate thermal simulation was performed using CFD by TheSys, a company specializing in the development of new heat exchangers, thermal simulation of performance and validation testing of heat exchangers and thermal systems. For several years, they have focused in particular on the development of additively manufactured heat exchangers.

The thermal performance simulation considered constant boundary conditions of 1 l/min flow rate and 60°C coolant inlet temperature.* The heat generation of 120 W by the CPU was modelled as a constant heat flow density in the contact area.

The benchmark cooler was simulated with the assumption of a pure copper body. In reality, only some parts of the cooler were made of pure copper; other materials were used as well. Considering that copper has one of the highest thermal conductivities the performance prediction of the benchmark cooler is optimistic.

The first design of the 3D printed cooler was realized within 8 working days. After evaluating the simulation results, TheSys implemented two key improvements into the design. The pin geometries above the base plate were optimized and the wall geometry was adapted. Both measures adjusted the heat distribution and ultimately achieved the targeted low surface temperature at the contact area of the CPU, while also reducing the pressure drop. After just one design iteration, the surface temperature distribution, cooling performance and pressure drop matched those of the benchmark cooler closely.

For the benchmark cooler, there is an impact flow with a stagnation point at the CPU center line area. Outside of the CPU footprint, the flow velocities are constant, inducing a pressure drop in areas without heat input.

For the 3D printed cooler, the local coolant flow velocities are adapted to the local heat flow density. As a result, there is an optimized impact flow with a stagnation point at the CPU center line area and higher velocities beneath, balancing the high heat flow density in this particular area. The velocities are reduced to less than 50% outside of the CPU contact area. A small vortex still forms in the outlet, meaning that there remains potential for some further design optimizations.

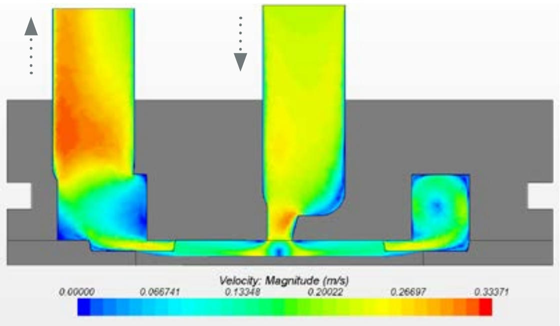


Figure 5a

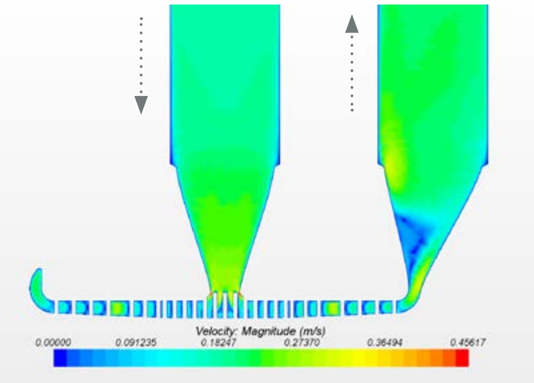


Figure 5b

Coolant flow at CPU cooler central plane

Figure 5a: Simulation of velocities for benchmark CPU cooler in central plane
Figure 5b: Simulation of velocities for 3D printed CPU cooler in central plane

* The temperature of 60°C was chosen because it is typical for the new practice of using the waste heat from data centers for other practical purposes. It is reasonable to assume the comparison results are similar when working with lower coolant inlet temperatures that are typical for stand-alone gaming computers.

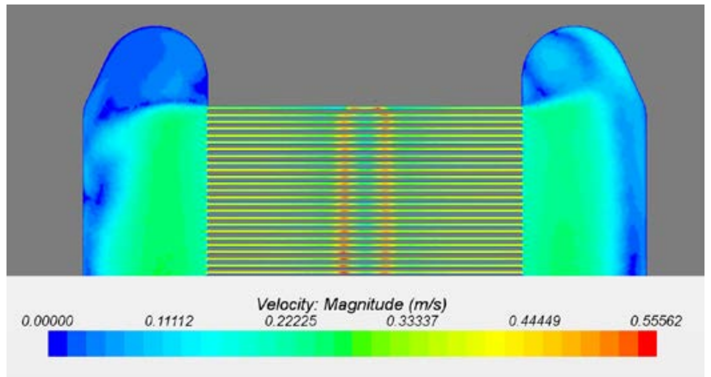


Figure 6a

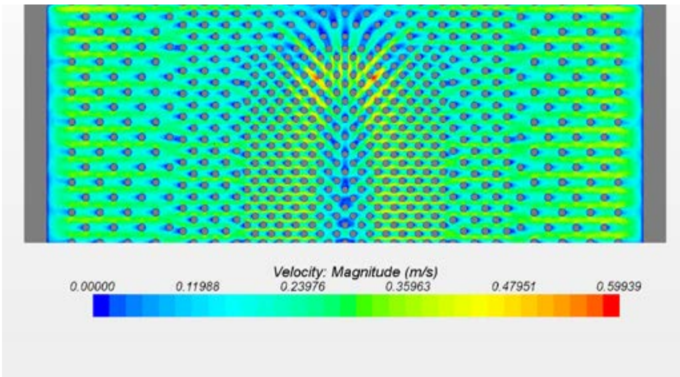


Figure 6b

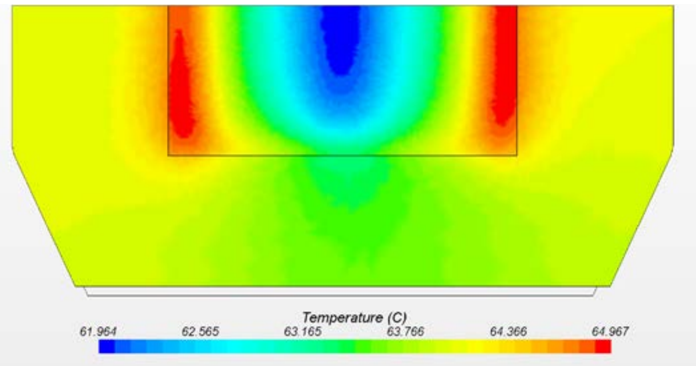


Figure 7a

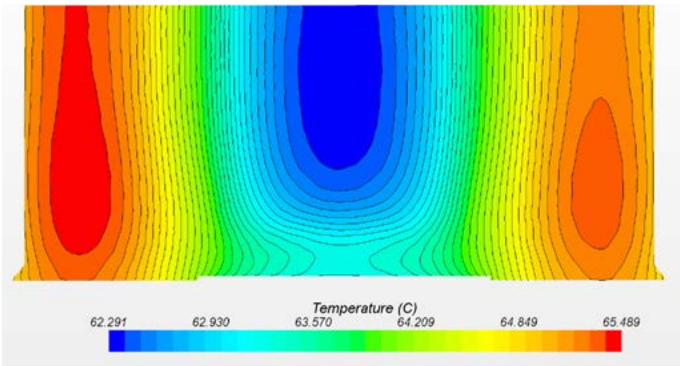


Figure 7b

Coolant flow at CPU cooler horizontal plane

Figure 6a: Simulation of velocities for benchmark CPU cooler in horizontal plane directly above the CPU
Figure 6b: Simulation of velocities for 3D printed CPU cooler in horizontal plane directly above the CPU

Temperatures at CPU surface across the base plate

Figure 7a: Simulation of surface temperatures for benchmark CPU cooler in horizontal plane directly above the CPU; CPU footprint marked as a rectangle
Figure 7b: Simulation of surface temperatures for 3D printed CPU cooler in horizontal plane directly above the CPU; CPU footprint is approximately the size of the whole base plate

Figure 8: Innovated gaming CPU cooler optimized for 3D printing, manufactured on a standard EOS M 290 machine in pure copper from Elementum 3D

CPU Cooler Size Decreased by 81% with 3D Printing

Comparing the surface temperatures in the contact area of the CPU shows that the minimum temperatures of both designs are similar. The internal pins in the 3D printed cooler were arranged to optimize heat rejection at the position of the main heat source.

The pressure drop increased slightly by 5.5% from 4.5 mbar (benchmark cooler) to 4.75 mbar (3D printed cooler).

With a single design iteration achieving performance equivalent to that of the benchmark 3D printed CPU cooler, the benefits are clearly visible:

⟶ The size of the cooler was reduced by 81% from 58 cm³ (benchmark cooler) to 10.8 cm³ (3D printed cooler).

⟶ The weight of the cooler was reduced by 75% from 450 g (benchmark cooler) to 107 g (3D printed cooler made of copper).

⟶ The weight was even reduced by 93% to 32 g when using aluminum for the 3D printed cooler and accepting a slight increase of the surface temperature by 0.4°C.

Key advantages
Innovative cooler for gaming CPUs made by 3D printing

same cooling performance on less space with less weight	can be easily customized to individual chip thermal footprint	can be adapted to any shape cavities	the absence of weld seams reduces the risk of leakage

Results for both designs

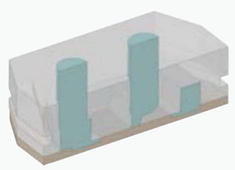
	Benchmark CPU cooler	3D printed CPU cooler (copper)	3D printed CPU cooler (aluminum)
Medium temperature at middle of base plate (°C)	62,0	62,3	62,7
Pressure drop (mbar)	4,5	4,75	4,75
Volume (cm³)*	58	10,8	10,8
Weight (g)**	450	107	32
Design adaptability	low	high	high
Material	copper, steel, nickel-plated brass, POM	copper	aluminum
Pictures			
Volume	100 %	–81 %	–81 %
Weight	100 %	–76 %	–93 %

Table 1: Comparison of the technical performance between the benchmark CPU cooler and the 3D printed CPU cooler built in copper and aluminium, respectively.

*The volume without legs to mount the cooler on the chip has been compared. **Weight including legs.

The innovations presented above can be immediately translated into commercial products. Given a known, inhomogeneous heat flow density in the CPU contact area, 3D printed designs can be specifically tailored to the heat distribution. This is impossible in practice for conventionally designed coolers because of the ramifications for the production chain, but tailoring to specific CPUs or other chips is easy to accomplish with additive manufacturing. The changes in the production chain are purely digital. Customized parts can be released into production without human interaction or change-over costs.

New Design Freedom Paves the Way for Radical Innovations

In just a few days development time, the cooling performance of the best-in-class conventional CPU cooler was equaled with a 3D printed cooler that only requires a fraction of the space. The key was to combine the expertise of TheSys in thermal solutions with the additive manufacturing experience of AM Metals and EOS. Eliminating the inhibiting effects of conventional manufacturing opens a door to further miniaturization and radical new concepts like biomimetics.

Once the creative power of thermal engineers has been unleashed by overcoming the dogma of conventional manufacturing, radical innovations will be just moments away.
For example, we are surrounded by designs optimized over millions of years of evolution that can be translated into ingenious technical designs for thermal management. Thanks to 3D printing, we are now capable of manufacturing these geometries. Figure 9 shows a sea anemone that evolved to maximize its surface area to filter out nutrients from passing water. Perhaps this structure would be ideal for a low-flow heat exchanger?

In fact, there are countless applications where heat transfer space comes at a premium. Just consider gaming laptops, HP LEDs, lasers, autonomous driving, power electronics [4], chemical micro reactors. We believe that additive manufacturing can bridge the gap between current market demands for miniaturized thermal management solutions and future technologies that might circumvent the problem in a fundamentally new way.

Inspired by sea anemones

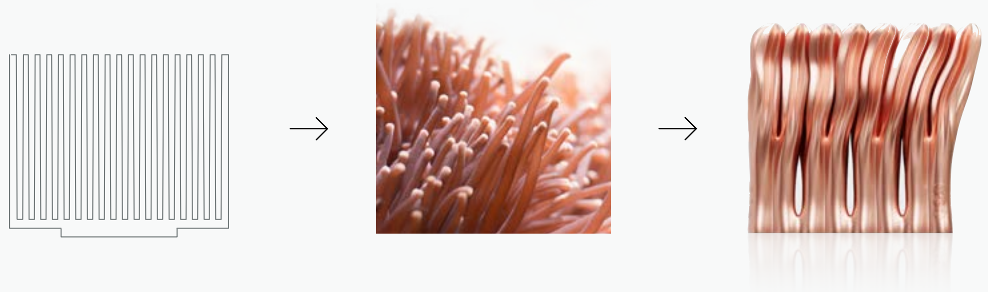


Figure 9: Biomimetic heat exchanger design inspired by sea anemones

Left: Conventional design passive heat exchanger
Middle: Anemone structures are optimized for large surface areas at low water flows. © Mat Reding / Unsplash
Right: Future passive heat exchangers might look more a sea anemone than a comb thanks to the freedom of design offered by additive manufacturing. © EOS, Design by Moritz Heller

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Dr. Matthias Hoeh
Senior Business Development Manager

Matthias is scouting applications and developing business models for industrial 3D printing. One of his focus topics is thermal management innovations. He is responsible for developing holistic solutions to realize the business ideas of EOS' customers.

In his early career Matthias was trained as a physicist and spent four years as a researcher at Heidelberg University, Germany. He then joined Konica Minolta as a product manager, responsible for in-line test systems in electronics manufacturing. Since more than 15 years he is also active as an entrepreneur in various fields. In 2016 Matthias entered the world of industrial 3D printing and joined EOS.

Contact:
matthias.hoeh@eos.info

Dr. Peter Ambros
TheSys GmbH
www.thesys-engineering.de

Contact:
p.ambros@thesys-engineering.de

Dr. Florian Wendt
AM Metals GmbH
www.am-metals.de

Contact:
florian.wendt@am-metals.de

EOS GmbH
Electro Optical Systems
Corporate Headquarters
Robert-Stirling-Ring 1
82152 Krailling/Munich
Germany

Phone +49 89 893 36-0
info@eos.info

www.eos.info

If you have any remarks or comments, please get in touch.