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GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

**A PARAMETRIC INVESTIGATION OF TOPOLOGY
OPTIMIZATION IN HEAT SINK DESIGNS**

ISMET CAN BIRINCI

A THESIS OF MASTER SCIENCE
DEPARTMENT OF MECHANICAL ENGINEERING

ADVISOR: ASSIST.PROF. DR. RECEP ÖNLER

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LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

SOĞUTUCU TASARIMINDA TOPOLOJİ
OPTİMİZASYONUNUN PARAMETRİK İNCELEMESİ

İSMET CAN BİRİNCİ

YÜKSEK LİSANS TEZİ
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MAYIS 2025



MASTER of SCIENCE JURY APPROVAL FORM

A thesis submitted by İsmet Can Birinci, defended on 28/05/2025 before the jury formed with the 10/02/2025 date and 2025/10 numbered decision of the GTU Graduate Administration Board, has been accepted as a MASTER of SCIENCE thesis in the Department of Mechanical Engineering.

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ABSTRACT

Cooling heated components, environments, etc., across various sectors is a necessity. To meet this need, coolers are designed in different ways using various production methods. The design methods for coolers depend on their types, and each method has its own mathematical framework. Today, coolers are generally designed and manufactured using traditional methods that have been in use for a long time. However, in critical areas, special solutions may be required. There may be a need for coolers that occupy less space, lighter, and provide better heat transfer, thus improving cooling performance. In such cases, topology optimization can be used for cooler designs. Since the geometries obtained through topology optimization are usually not manufacturable using traditional methods, metal additive manufacturing is employed. This manufacturing method enables the production of complex structures, providing great freedom for designers. It allows the creation of shapes that would be impossible to achieve through conventional methods, even with materials that are difficult to process, such as stainless steel or titanium. This study focuses on cooler design through topology optimization. Previous optimization studies were reviewed, and the results of the study were validated by replicating those works. The impact of changing various parameters on the results was examined. Additionally, the necessary parameter adjustments were made to ensure that the obtained geometries could be manufactured using metal additive manufacturing. The study was performed using the COMSOL software.

Keywords: Topology Optimization, Additive Manufacturing, Heat Sink

ÖZET

Çeşitli sektörlerde ısıtılmış bileşenlerin, ortamların vb. soğutulması bir gerekliliktir. Bu ihtiyacı karşılamak amacıyla soğutucular, farklı üretim yöntemleri kullanılarak çeşitli şekillerde tasarlanmaktadır. Soğutucu tasarım yöntemleri, kullanılan soğutucu tipine bağlı olarak değişmekte olup her birinin kendine özgü matematiksel altyapısı bulunmaktadır. Günümüzde soğutucular genellikle uzun süredir kullanılan geleneksel yöntemlerle tasarlanmakta ve üretilmektedir. Ancak kritik uygulamalarda özel çözümler gerekebilmektedir. Daha az yer kaplayan, daha hafif ve daha iyi ısı transferi sağlayarak soğutma performansını artıran soğutuculara ihtiyaç duyulabilmektedir. Bu tür durumlarda, soğutucu tasarımlarında topoloji optimizasyonu kullanılabilir. Ancak topoloji optimizasyonu sonucunda elde edilen geometriler çoğunlukla geleneksel yöntemlerle üretilemez yapıdadır. Bu nedenle, metal katkı imalatı (metal 3D yazıcılar) tercih edilmektedir. Bu üretim yöntemi, karmaşık yapıların üretilmesine olanak tanıyarak tasarımcılara büyük bir özgürlük sunmaktadır. Paslanmaz çelik veya titanyum gibi işlenmesi zor malzemelerle dahi, geleneksel yöntemlerle elde edilmesi imkânsız şekillerin üretimi mümkün hale gelmektedir. Bu çalışma, topoloji optimizasyonu kullanılarak soğutucu tasarımı üzerine odaklanmaktadır. Önceki optimizasyon çalışmaları incelenmiş ve bu çalışmalar tekrarlanarak elde edilen sonuçlar doğrulanmıştır. Ayrıca çeşitli parametrelerin sonuçlara etkisi araştırılmıştır. Elde edilen geometrilerin metal katkı imalatı ile üretilabilir olmasını sağlamak amacıyla gerekli parametre ayarlamaları yapılmıştır. Çalışmalar, COMSOL yazılımı kullanılarak gerçekleştirilmiştir.

Anahtar Kelimeler: Topoloji optimizasyonu, Eklemeli İmalat, Soğutucu

ACKNOWLEDGEMENTS

I will raise the flag he left me until my last breath, to the person who gave it to me, my father.



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LIST OF SYMBOLS AND ABBREVIATIONS

k	: Thermal Conductivity
T	: Temperature
Q	: Volumetric Heat Generation
Ω	: Design Domain
f_{obj}	: Objective Function
k_{SIMP}	: Thermal Conductivity as Function Of
ρ_{des}	: Design Density
k_s	: Thermal Conductivity of Solid Material
n	: Penalization Factor
γ	: Volume Fraction
k_{min}	: Chosen Thermal Conductivity Value
A	: Area Of Design Domain

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1 INTRODUCTION

Throughout history, humans have designed systems to make their work easier, to accomplish tasks beyond human capability, and to produce energy, among other reasons. These systems have taken shape in accordance with the known technologies of their time. For instance, a comparison between past and present vehicles can be made. A vehicle produced in the 1980s typically features a boxier and bulkier geometry when viewed from the outside. Engines were less efficient, braking systems were different—many such differences can be listed. In contrast, today's vehicles are designed with much more emphasis on aerodynamics and efficiency. Taking this example further, just as there is a need for such improvements in the automotive sector, cooling systems are also essential in industries such as aviation, aerospace, energy, and maritime. Although the heat sinks used in these sectors may vary in form, their purpose remains the same. Depending on the system in which they operate, heat sinks can take on different shapes and structures. Sometimes, they appear as massive components; other times, they can be as small as the tip of a finger. Their design can vary entirely based on the boundary conditions of the system, and different types of cooling methods may be applied. In systems where air is used as the cooling medium, designs can rely on forced or natural convection to cool the targeted heat source. Alternatively, if liquid cooling is intended, tubular heat exchanger designs may be implemented. Each type of heat sink may be influenced by different parameters. For instance, in tubular heat exchangers, parameters such as the type of coolant liquid, tube diameter, number of tubes, spacing between plates, and flow rate of water play critical roles. Each of these factors is considered during the design process along with boundary conditions and specific requirements

1.1 Heat Sinks

Today, a wide variety of systems are being designed for numerous different purposes. In some of these systems, heat exchangers are a core part of the system, while in others, they function as supporting components. Heat sinks are components specifically designed to cool a particular part or environment. In many different systems, cooling must be addressed in various ways. Depending on the system and its application area,

the cooling method, required space, size, and type of cooling system can vary significantly.

For example, in the maritime industry, large shell-and-tube heat exchangers have been developed as a solution. In these systems, the fluid to be cooled flows through the inner tubes, while the cooling fluid passes around them externally. On the other hand, chip cooling requires smaller heat sinks, which are typically designed to benefit from natural convection. Many other examples like these exist across different industries.

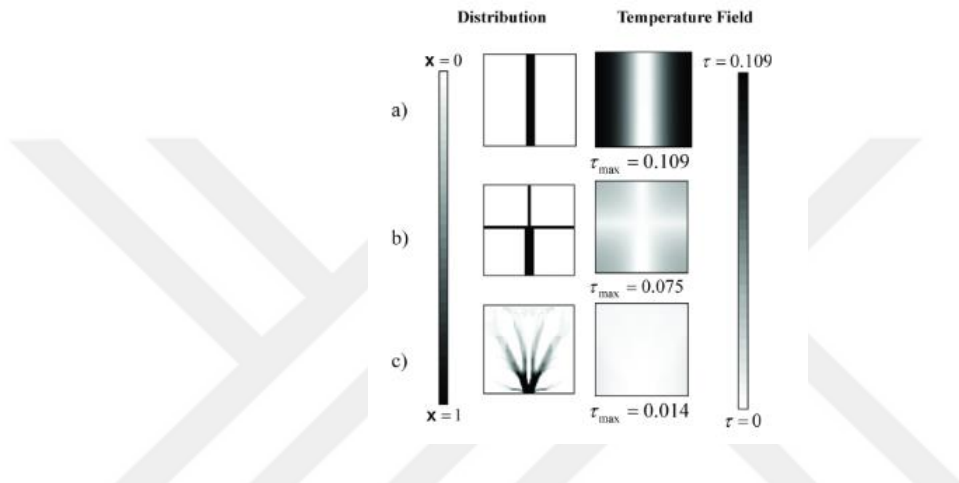


Figure 1. 1: Different type of material dissipation and thermal performances [3].

In this study, the design of heat sinks through topology optimization and the effects of various parameters on the design throughout the process were examined. Topology optimization can be defined as a design improvement process that aims to achieve the best possible outcome in line with predefined objective function(s), while adhering to specific boundary conditions and parameter constraints. Through iterative processes, the system attempts to converge on the optimal solution using existing equations and data.

Topology optimization can be performed using different methods and solution techniques, each with its own advantages and disadvantages. Studies analyzing these aspects can be found in the literature [1]. Heat sinks designed using this method are expected to outperform conventional ones in terms of weight, efficiency, or whichever criterion is set as the objective (as defined in the objective function). In fact, every design inherently carries this concern—every component is expected to perform its function in the best possible way. Topology optimization enables this by following the

defined objectives in the form of equations. Additionally, factors like cost can also be incorporated into the objective function [19].

This method can play a life-saving role in critical applications. For instance, it can be used in the cooling systems of turbofan engine blades. One of the greatest obstacles to achieving the targeted engine power in such engines is the high temperature. The air flowing from the compressor to the turbine blades can reach temperatures high enough to melt the material from which the blades are made. Therefore, cooling the blades is of utmost importance. Topology optimization can play a significant role in designing the internal cooling structures of these blades. With optimization, a heat sink within the blade can be designed in a way that maximizes thermal dissipation. Similarly, topology optimization can be utilized to design highly efficient cooling systems for battery applications [4].



Figure 1. 2: Designed heat sink with topology optimization [2].

In this study, using topology optimization, heat sink designs were developed for cooling a pipe that contains a heat source flowing through it. The heat sink was placed between the central heat source and the outer wall of the pipe. Each of the resulting designs was created by modifying a different parameter. These modified parameters are those involved in the equations of the topology optimization process. A detailed schematic of the problem can be seen in the accompanying figure.

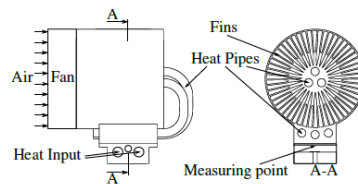


Figure 1. 3: Designed heat sink with topology optimization [18].

This study investigates the impact of the parameters in the equations of topology optimization on the designs. The effects of these parameters on the shapes and objective functions were examined. Additionally, each design was analyzed using finite element analysis while adhering to the boundary conditions of the main problem. The goal was to evaluate whether the behavior of the objective function aligns with the results of the analysis. Previous studies in this direction were also referenced [20][2][3].

1.2 Literature Review

Various studies in the literature have explored different aspects of thermal topology optimization. There are studies focusing on the influence of parameters affecting optimization on both geometry and performance. Sharar, Wilson, and Leff [20], using the SIMP method in COMSOL, investigated how parameters such as the Helmholtz filter, penalization factor, and heat transfer coefficient affect design and performance by varying them within specific ranges. In their study, the objective function was defined as minimizing the solid region while maximizing thermal conductivity. As the heat transfer coefficient defined over the design domain increased, lower infill ratios yielded lower average temperatures. Smaller Helmholtz filter values resulted in "wetter" areas—i.e., the heat spread over a broader area through thinner branches. However, due to manufacturability issues, they recommended that the Helmholtz filter value be kept within a specific range. Similarly, Dirker and Meyer [3] compared different parameters and their effects. In their work, three distinct objective functions were defined: one related to maximum temperature, one to average temperature, and another inspired by the objective functions used in Gersborg and Hansen's studies. They analyzed how different penalization factor scenarios—fixed versus increasing—affected these objective functions, including their impact on gray regions and cooling performance. Additionally, the change in performance over iterations was examined. For example, one configuration had fewer gray regions in the 40th iteration compared to the 100th. The influence of mesh density was also evaluated to determine the optimal mesh resolution for best performance. In another study presented at a conference by Burger, Dirker, and Meyer [22], the effect of the number and position of seed locations for cooling a cubic domain was investigated. Prior to that, they

examined the impact of mesh resolution and iteration count, defining a non-dimensional temperature metric for performance evaluation.

Wu et al. [4] developed a cold plate for electric vehicle battery packs using a pseudo-3D topology optimization approach, where separate thermal and hydraulic objective functions were combined into a weighted formulation. Their methodology included a grid independence study to reduce computational cost and explored the impact of penalty coefficients, Reynolds number, and weighting factors on the resulting designs. One optimized geometry was further evaluated through 3D CFD simulations. Building on this foundation, Wang et al. [12] refined the approach by introducing a multi-objective optimization framework specifically tailored for EV battery thermal management systems. Their topology-optimized designs outperformed traditional serpentine channel configurations, such as those in the GM Volt platform, demonstrating significant gains in both thermal resistance and energy efficiency. In parallel, Özgüç et al. [7] addressed the challenge of dynamic thermal loads by proposing a flow-shifting microchannel topology. This innovative design enabled localized cooling through selective inlet activation and achieved superior thermal performance across varying workload scenarios, offering a promising solution for heterogeneous thermal environments in next-generation electronics and battery systems.

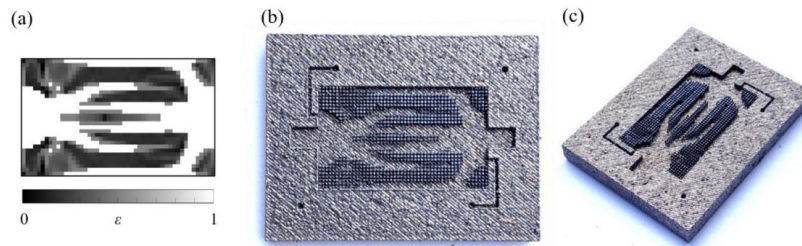


Figure 1. 4: Heat sink obtained by homogenization approach [5].

Ozguc and Teague [5] utilized the homogenization method to optimize a heat sink. The objective function combined thermal resistance and pressure drop, each assigned a weight coefficient. The study analyzed the influence of grid size on thermal resistance and pressure drop, as well as how the number of iterations affected the objective function. While lower weight coefficients reduced pressure drop, they increased thermal resistance, leading to poorer thermal performance. It was observed

that smaller grid sizes improved performance; however, manufacturability imposed a lower limit on the grid size.

There are also comparative studies in the literature evaluating designs obtained via topology optimization against those derived from other optimization techniques. Lange et al. [18] compared a design obtained through parametric optimization with one from topology optimization for a heat sink embedded within a round pipe under forced convection. The objective function in the topology-optimized model aimed to enhance heat transfer. As a result, the topology-optimized design was both lighter and provided significantly better cooling performance than the parametrically optimized version. Notably, manufacturability was included directly in the objective function—a refinement compared to Sharar, Wilson, and Leff [20], who only mentioned manufacturability in terms of the Helmholtz filter. Xie et al. [19] also applied topology optimization to a heat sink under forced convection, where the objective function was defined as minimizing pressure drop and heat transfer performance was included as a constraint. Compared to a conventional straight-fin design using the same pump power, the topology-optimized geometry achieved 5.76% lower average temperature and a 49.2% increase in Nusselt number, owing to the generation of local high velocities. Li et al. [6] employed a multi-objective optimization framework for liquid-cooled heat sinks, combining thermal and hydraulic criteria. Their COMSOL-based models were validated experimentally, demonstrating that topology-optimized geometries significantly outperformed conventional parallel-channel designs in terms of both thermal resistance and Nusselt number.

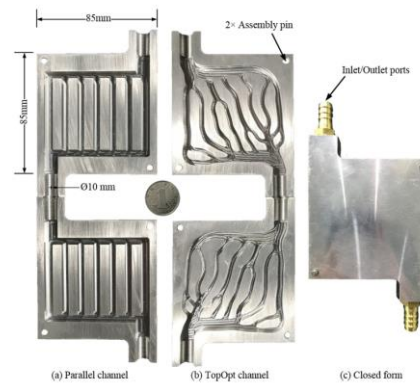


Figure 1. 5: Parallel channel and topology optimized heat sink prototypes [6].

Wu et al. [4], in the final stage of their work, compared a classical design with the topology-optimized one. Although the topology-optimized geometry outperformed the classical design in terms of temperature reduction, the latter was more efficient in terms of pressure drop at higher flow rates.

Høghøj et al. [16] applied topology optimization to shell-and-tube heat exchangers, employing an erosion-dilation interface definition method to handle dual-fluid modeling. Their 3D simulations demonstrated up to 113% improvement in heat transfer relative to baseline models. Yan et al. [17] advanced this with a unified density field and opposing permeability interpolations to isolate hot and cold flows in a single domain, supported by large-scale parallel simulations on OpenFOAM.

The literature also contains studies where the topology-optimized designs were fabricated and tested, followed by a comparison between simulation and experimental results. Subramaniam, Dbouk, and Harion [2] developed a heat sink through topology optimization, fabricated it, and then tested it. The mathematical modeling, design of the test setup, and comparison of CFD results with experimental data were presented. Due to the presence of gray regions in the optimization results that are not manufacturable in reality, it was emphasized that a filtering step is necessary before production. Although discrepancies were observed in temperature values near the edges—primarily due to heat loss at the boundaries—the simulation and experimental results converged in the central regions. Ozguc and Teague [5] also fabricated their topology-optimized design and compared simulation data with experimental measurements. While some deviations were noted, the overall agreement was strong. These deviations were attributed to factors such as rounded edges of fins in the fabricated model (as opposed to sharp edges in simulations) and surface roughness, which enhanced heat transfer but was not modeled. Ning et al. [9] also produced several LPBF-manufactured prototypes with differing objectives and validated them experimentally. Their topologies yielded thermal resistance reductions of up to 50% and demonstrated how additive manufacturing enables complex yet high-performing heat sink designs. Pilagatti et al. [10] explored similar themes by integrating manufacturing constraints directly into the optimization process across multiple design cases.

Zhou et al. [11] conducted one of the earliest industrial-scale implementations of combined conduction-convection optimization, using commercial tools (CATIA, Abaqus, Tosca). Their study incorporated design-dependent convection coefficients and validated results through SIMULIA and COMSOL models. In a similar vein, Pandey and Lee [15] applied pseudo-2D optimization to data center chip cooling systems, integrating advanced fin topologies (DOTO) and validating performance gains through coupled COMSOL–Fluent simulations.

Different solution methods have also been employed in thermal topology optimization. Zhang, Xu, and Gao [1] used the element differential method (EDM) and compared it with traditional methods across multiple benchmarks, analyzing metrics like time to assemble the matrix and time to solve equations, as well as convergence behavior. Wang et al. [14] compared the SAW and ε -constraint multi-objective optimization algorithms in microchannel heat sinks, finding that the ε -constraint method significantly reduced gray regions and improved convergence speed by over 40%.

Cattoni et al. [23] demonstrated the application of both gradient-based and adjoint solvers to optimize components in a molten salt fast reactor, revealing considerable reductions in thermal gradients and pressure drop. Erfani et al. [13] implemented SIMP-based optimization in packed-bed reactors containing monolithic catalysts and validated their designs through 3D modeling and COMSOL simulations. Despite increased pressure losses, conversion efficiency improved, highlighting the trade-offs inherent in such designs.

Some studies in the literature primarily focused on explaining the process of thermal topology optimization. For instance, Haertel, Engelbrecht, and Kurt [21] applied topology optimization to a two-dimensional coupled thermofluid model of a heat sink cooled by forced convection and described its procedural stages in detail.

In multiphase environments, Özgüç et al. [8] introduced a homogenization-based optimization approach integrated with a two-phase flow model. By tuning vapor quality constraints, their method enabled the design of structures effective under boiling conditions—a rarely addressed regime in prior topology optimization literature.

1.3 Heat Sink Design

Although a heat sink design based on topology optimization is developed in this study, it is important to note that the vast majority of heat exchangers and cooling components used today are still manufactured using conventional methods. It is possible to encounter various types of heat exchangers and heat sinks in the literature and in practice. These include tubular, plate-type, finned, and regenerative heat exchangers.

There are several approaches available for the design of conventional heat exchangers. The design process may be carried out manually through hand calculations; alternatively, the equations, variables, and design requirements can be implemented in a programming environment such as MATLAB, where the entire design procedure is performed computationally. Additionally, specialized commercial software packages are commonly used for this purpose. These packages frequently integrate Finite Element Method (FEM) and Computational Fluid Dynamics (CFD) tools.

In essence, conventional heat exchanger design is also a type of optimization process. The required performance criteria are defined, and the design parameters of the heat exchanger are adjusted accordingly. For instance, in a shell-and-tube heat exchanger, parameters such as the number of tubes, tube diameter, baffle spacing, and fluid velocity are subject to optimization in order to achieve the desired thermal performance. Similarly, in finned heat exchangers, parameters like fin type, length, width, and thickness must be optimized to obtain effective results.

Once the appropriate design approach is selected in conventional methods, the subsequent process primarily involves optimizing these design parameters to meet the performance requirements.

1.4 Topology Optimization

Designs are made based on needs. Whether it's a mechanical or thermal design, the requirements are clear, and the designs are made to meet these requirements. It is possible to create many different designs that meet the same requirements. For example, each water brand has different bottles that can carry the same volume of water. All of these different designs successfully fulfill the task expected from them,

which is to hold the water inside. There are countless examples from real life that we can give in both mechanical and thermal contexts.

Topology optimization is an optimization process used to determine the most effective material distribution or optimal design based on a predefined objective function and under a set of specified constraints. The objective function typically models goals such as improving heat transfer or reducing structural weight. Also known as the cost function, it may incorporate multiple equations corresponding to different performance criteria, each assigned a weighting factor to prioritize its importance. For instance, Wu, Li, and Zhi [4] used two objective functions—thermal and hydraulic—in their work and added a weighting coefficient to each.

Constraints in topology optimization can be defined in various ways, such as imposing volume fraction limits or minimum mesh size requirements. The key distinction between topology optimization and traditional design processes is that topology optimization aims solely to minimize the objective function, which allows for the generation of highly complex geometries. While traditional design methods often focus on improving specific geometric parameters within a fixed design space—as seen in heat sink applications—topology optimization allows complete geometric freedom.

Topology optimization is applicable across a wide range of industries and use cases. Mechanical or thermal components and systems can be significantly improved through this method. For example, a part used in an aircraft can be optimized to be lighter while maintaining its functional integrity. Similarly, a cooler with a defined volume can be redesigned to dissipate more heat within the same volume.

The topology optimization process follows a set of defined steps that ultimately lead to the most suitable material distribution for the desired performance. The most commonly used method involves density distribution, where each finite element is assigned a value between 0 and 1 to indicate whether it is void or solid.

The process begins with the definition or importation of the geometry to be optimized. This geometry can either be created within the analysis software or imported from another CAD program. The design domain is then identified, and the material

properties are defined. Next, boundary conditions are applied to the geometry. In thermal problems, this includes definitions such as heat source, heat flux, or temperature constraints. In mechanical problems, supports and loads with specific magnitudes and directions are defined.

Following this, the geometry is meshed, and the finite elements are generated. Mesh density is important for solution accuracy and computational efficiency. While a finer mesh yields more accurate results, it also increases computation time. Therefore, determining the optimal mesh density is essential and will be discussed later in this study.

After meshing, a finite element analysis (FEA) is conducted to evaluate the behavior of the material. A sensitivity analysis is then performed based on the objective function and constraints. The geometry obtained from the sensitivity analysis is filtered to eliminate checkerboard patterns and to ensure manufacturability. Convergence is subsequently checked. If the results have not converged to the desired threshold, the process repeats until convergence is achieved.

There are various algorithms and methods used in topology optimization, which are detailed below. In this study, the SIMP method is employed.

Various methods have been developed in the field of topology optimization, each with distinct advantages and limitations depending on the application area. One of the most commonly used approaches is the SIMP (Solid Isotropic Material with Penalization) method. In this technique, each element is assigned a density value between 0 (void) and 1 (solid), and the material properties are interpolated accordingly. A penalization factor is introduced to discourage intermediate (gray) regions. SIMP offers high computational efficiency and is widely supported by commercial software. However, the presence of non-manufacturable gray areas often necessitates the use of filtering techniques, which is a major limitation.

Another method, ESO (Evolutionary Structural Optimization), is a heuristic-based approach that begins with a fully solid design domain and progressively removes elements that carry low stress. Its ease of implementation and conceptual intuitiveness

are notable advantages. On the other hand, it lacks a guarantee of reaching a global optimum and may become trapped in local minima.

The Level-Set method offers a more advanced representation by implicitly defining the geometry through the zero level set of a continuous scalar field. This technique is advantageous for generating smooth and well-defined boundaries, which enhances manufacturability. Nevertheless, its high computational cost and limited capability to capture topological changes remain significant drawbacks.

Lastly, homogenization-based methods establish a link between microstructures and macroscopic behavior, making them particularly suitable for porous or composite materials. While these methods are highly effective for analyzing multi-phase systems, their complex implementation and requirement for advanced mathematical knowledge limit their broader applicability.

The geometries resulting from topology optimization are often highly complex. As such, conventional manufacturing techniques are frequently inadequate for their fabrication. This makes metal additive manufacturing (AM) a prominent solution. AM enables the production of complex geometries that would otherwise be unfeasible. However, even with AM, certain designs may still be impractical to fabricate due to extremely fine features or unsupported structures.

To address this, specific constraints can be incorporated into the optimization process. For instance, the minimum mesh size can be adjusted according to the laser diameter used in AM. In some studies, a manufacturability function is defined and integrated into the objective function. Lange [18], for example, included a manufacturability-related function alongside the heat transfer objective in his study. Similarly, in the study by Ozguc [5], it was observed that pin fins smaller than 0.245 mm failed during fabrication, and the mesh size was adjusted accordingly.

These considerations highlight the importance of integrating design and manufacturing constraints early in the optimization process to ensure that the resulting geometry is not only high-performing but also feasible to produce.

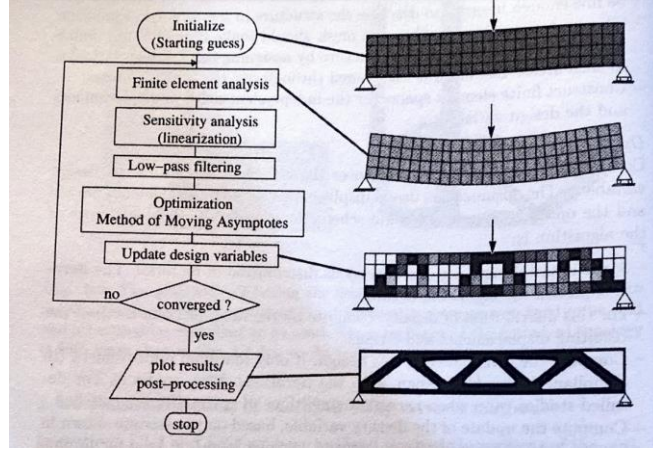


Figure 1. 6: Example of topology optimization scheme [5].

It has been demonstrated through various studies that topology optimization yields more effective results compared to other methods. One such example is presented in the study by F. Lange, C. Hein, G. Li, and C. Emmelmann [18]. In this work, both topology optimization and parametric optimization were applied to the design of a cooler, taking into account the constraints imposed by the Selective Laser Melting (SLM) manufacturing process. Subsequently, a performance comparison was made between the two resulting geometries.

As shown in Table 1.1, the geometry obtained through topology optimization exhibited superior performance when compared to the parametrically optimized counterpart. Furthermore, while the weight of the parametrically optimized cooler was 0.17 kg, the geometry produced via topology optimization weighed only 0.134 kg. Therefore, in the context of the addressed problem, topology optimization resulted in a design that was not only lighter but also more efficient in terms of thermal performance.

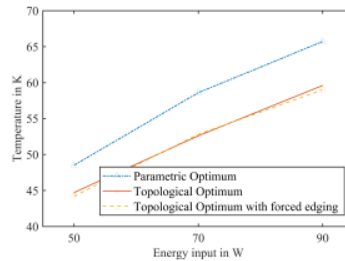


Figure 1. 7: Parametric-topology optimized cooler performance comparison [18].

1.5 Production Methods And Metal Additive Manufacturing

From past to present, conventional manufacturing methods such as forging and casting have been widely employed in the production of industrial components. With the advancement of technology, additional processes such as welding, turning, milling, and CNC machining have become standard in manufacturing practice. In heat exchangers designed using traditional approaches, classical manufacturing techniques remain applicable. For example, in shell-and-tube heat exchangers, bending processes are used to shape the tubes; welding is employed to attach the tubes to the plates and to assemble the external shell. Furthermore, auxiliary components often require CNC turning or milling operations. Surface imperfections arising from welding are typically corrected through grinding.

However, the production of geometries obtained via topology optimization using conventional manufacturing methods is highly improbable. While this depends partly on the specific geometry, in general, the complex and irregular forms generated through topology optimization can only be manufactured using metal additive manufacturing (AM) technologies.

Metal additive manufacturing is a production technique that enables the fabrication of highly complex geometries that are otherwise difficult or impossible to realize using traditional methods. It allows for the processing of materials such as titanium, aluminum, and stainless steel—materials that are often challenging to machine using conventional processes—into intricate and optimized structures. This characteristic makes metal AM particularly advantageous for manufacturing parts designed via topology optimization.

Among the metal AM technologies, techniques such as Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS), and Electron Beam Melting (EBM) are prominent. These processes involve the layer-by-layer melting of metal powders using a laser or electron beam to construct the final geometry.

2 TOPOLOGY OPTIMIZATION OF HEAT SINK

In this study, a heat sink design has done by using topology optimization. The effects of parameters and boundary conditions to optimized geometry and results has been investigated. Mathematical model examined.

2.1 Governing Equations

Initially, optimization problem must be defined.

$$\text{minimize } f_0(x) \quad (2.1)$$

$$\text{minimize } f_i \leq 0, i = 1, \dots, m \quad (2.2)$$

$$x_j^{\min} \leq x_j \leq x_j^{\max}, j = 1, \dots, n \quad (2.3)$$

f_0 is the objective function, f_i are behavior of constraints, m is the number of constraints and x is a vector of n design variables, x_j

To solve steady state heat transfer problem, Fourier's Law has been used

$$-\nabla \cdot (-k \nabla T) = Q \quad (2.4)$$

In this equation k represents thermal conductivity, T is the temperature and Q is the volumetric heat generation.

To obtain objective function, conditions has to be determined. In this problem which we worked on, there is no fluid flow. Because of that, effect of fluid flow didn't added objective function. The objective function must be a equation that keep temperature difference minimum in the design domain Ω , in the effect of constant heat generation. With the other words, thermal conductivity of the design domain must push maximum.

$$f_{obj} = \int_{\Omega} k(\nabla T)^2 d\Omega \quad (2.5)$$

2.2 Topology Optimization

To do topology optimization, SIMP material distribution model has been used, by adhering objective function and constraints. To use this model, ρ_{des} parameter has defined. This parameter able to take values 0 and 1. If a finite element takes 0 value, that means this element is fluid or no material, if it is 1, that means solid. To eliminate intermediate densities and forcing them to be material ($\rho_{des} = 1$) or no material ($\rho_{des} = 0$) penalization scheme has used. Since intermediate densities has no equivalent in real, these scheme must be use. To involve penalization scheme to the objective function thermal conductivity, k , has redefined as function of ρ_{des} . This function is represented as k_{SIMP} .

$$f_{obj} = \int_{\Omega} k_{SIMP} (\nabla T)^2 d\Omega \quad (2.6)$$

SIMP (solid isotropic material with penalization) rule has applied to the k_{SIMP} .

$$k_{SIMP} = (k_s - k_{min}) \cdot \rho_{des}^n + k_{min} \quad (2.7)$$

In this equation k_s is the thermal conductivity of solid material, k_{min} is value that must be chosen much smaller than k_s and n is the penalization factor. The heat sink which will obtain with topology optimization will be cooled by air. To provide air flow by passing air through the heat sink, the area of the heat sink in the domain must be restricted. This restriction has indicated below :

$$0 \leq \int_{\Omega} \rho_{des}(x) d\Omega \leq \gamma A \quad (2.8)$$

3 COMPUTATIONAL MODELING

3.1 Model Validation

For model verification, the example model presented in Dr. Aidan Wimshurst's Computational Fluid Dynamics Fundamentals Course 2 lecture notes was used. In this section, the mathematical modeling of the system was carried out step by step. A two-dimensional steady-state diffusion equation was employed in the modeling. Subsequently, as demonstrated in the same course, the mathematical formulations were developed and the corresponding matrix was constructed. Finally, the problem was solved using software such as MATLAB and Excel.

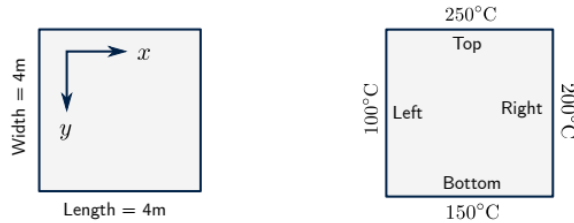


Figure 3. 1: Model description [24].

The model is as described above. A square domain with a side length of 4 meters was modeled. The right edge was set to a constant temperature of 200°C, the top edge to 250°C, the left edge to 100°C, and the bottom edge to 150°C. The thickness of the model was defined as 0.1 meters. The thermal conductivity of the material used in the model is 100 W/m·K. Additionally, a uniform heat source of 1000 W/m³ was applied throughout the material. To simplify the hand calculations in the example above, each corner was divided into four elements. The entire model was divided into a total of 16 elements. This study was also conducted in the COMSOL software under the same boundary conditions. After defining the necessary boundary conditions and material properties, the analysis was run.

3.2 Comparative Graphs and Error Analysis

The figures below present the graphical representation of the results obtained from the numerical analysis, alongside the graphical output of the analysis performed using the COMSOL software.

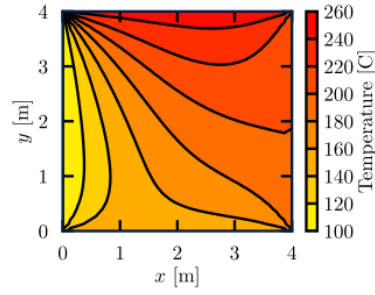


Figure 3. 2: Analysis result from notes [24].

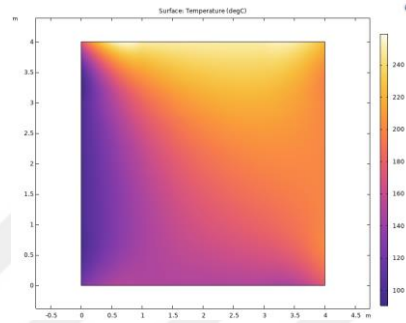


Figure 3. 3: Analysis result from COMSOL.

The model was divided into 16 elements. The temperature values at the center of each of these 16 elements, obtained from both the manual analysis and the COMSOL simulation, are presented in the table below.

Table 3. 1: Central temperature values of elements from notes [24].

	0.5	1.5	2.5	3.5
0.5	178.75	221.48	232.41	224.97
1.5	141.02	186.25	205.58	207.41
2.5	130.09	166.92	186.25	196.48
3.5	132.53	155.09	166.02	178.75

Table 3. 2: Central temperature values of elements from COMSOL analysis.

	0.5	1.5	2.5	3.5
0.5	176.8125	223.8875	232.9875	223.4125
1.5	134.33	184.355	204.5975	204.5725
2.5	125.225	163.925	184.1725	195.4725
3.5	130.2075	153.4575	162.5625	176.8125

The percentage error of each value is presented in the table below.

Table 3. 3: Percentage differences of the center temperatures.

	0.5	1.5	2.5	3.5
0.5	1.08%	-1.09%	-0.25%	0.69%
1.5	4.74%	1.02%	0.48%	1.37%
2.5	3.74%	1.80%	1.12%	0.51%
3.5	1.75%	1.06%	2.08%	1.08%

As can be seen from the error percentages above, the deviations are sufficiently small to be considered negligible. Therefore, it can be concluded that the model has been successfully validated.

3.3 Numerical Stability and Mesh Independence Study

This study aims to observe the extent to which mesh size influences the simulation results. Specifically, it investigates how different mesh resolutions affect the average temperature obtained from the analysis.

Since the analysis conducted in this study is not particularly complex, changes in mesh size did not lead to any observable variation in the average temperature. Whether a single element was divided into 4, 100, or even 500 sub-elements, the average temperature remained consistently at 180.62°C. Variations that typically occur at nodal points were not observed in this case. However, it is undoubtedly very likely to encounter such variations in more complex geometries.

3.4 Problem Definition for Topology Optimization

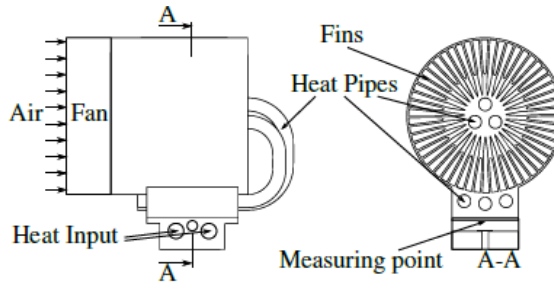


Figure 3. 4: Problem definition.

From this point onward, the details of the problem to be subjected to topology optimization will be introduced, followed by a step-by-step analysis using the

COMSOL software. Some parameters in the previously defined topology optimization equations will be modified, and their effects on the design will be investigated. Furthermore, the impact of the newly generated designs on the simulation results will be examined.

The schematic of the model to be studied can be seen in Figure 3.4. As illustrated in the figure, the system consists of a heat sink that is cooled by air. A heat source passes through the center of the heat sink, and an outer wall encloses the structure. In this study, topology optimization will be applied to the region between the heat source and the outer wall, i.e., the area through which air flows. The objective of the topology optimization is to achieve the best possible cooling performance. The equation that governs this objective is given as Equation 2.6. This equation will be implemented in the software, and the goal is to obtain the most efficient heat sink design that satisfies the defined constraints.

3.5 Importing Material Coefficients For Topology Optimization

The analysis will begin with the definition of material properties. In this stage, the material parameters are manually defined within the Definitions section of the COMSOL software. These defined coefficients will later be utilized in the formulation of equations throughout the subsequent steps of the analysis. The material parameters defined at this stage can be seen in Equation 2.7.

Table 3. 4: Material coefficients.

Coefficient Name	Value	Description
ro_kati	2700[kg/m ³]	
ro_hava	1.205[kg/m ³]	
k_kati	119 [W/(m*K)]	ks mentioned in eq 2.5
k_hava	0.1 [W/(m*K)]	kmin mentioned in eq 2.5
Cp_kati	1060 [J/(kg*K)]	
Cp_hava	0.1 [J/(kg*K)]	

The values are listed in above. In analysis, density and specific heat capacity also defined as function of ρ_{des} . Because of that, the coefficients defined for the thermal conductivity coefficient are also defined for the mentioned coefficients. In addition to the material coefficients, the parameters to be used for topology optimization are also defined in the Definitions section of the COMSOL software. These parameters will be modified in later stages of the study, and their effects will be examined. Furthermore, in the upcoming analyses, a parametric Sweep will be used to perform parameter variations and simulations more efficiently. The parameters defined in this step will also be utilized in the formulation of the governing equations in subsequent stages.

Table 3. 5: Coefficients for optimization and mesh.

Coefficient Name	Value	Description
n	3	penalization factor
mbmax_kati	2e-4[m]	maximum mesh size
mbmin_kati	1e-4[m]	minimum mesh size
filtreleme_radyusu	0.00025	filtering radius
hacim_orani	0.5	volume fraction
A	6.1016E-4 [m^2]	design domain area

3.6 Importing Parameters

In this study, the SIMP (Solid Isotropic Material with Penalization) method was used as the material distribution approach. To implement the SIMP method, Equation 2.7 must be applied. Therefore, properties such as density, heat capacity, and thermal conductivity must be defined as functions of the design variable, as outlined in Equation 2.7. In this section, these properties have been defined in the software as functions of the design variable.

Table 3. 6: Parameters for SIMP.

Parameter	Definition	Unit
k_simp	$k_{hava} + (k_{kati} - k_{hava}) * dtopo1.theta^n$	W/(m·K)
ro_simp	$ro_{hava} + (ro_{kati} - ro_{hava}) * dtopo1.theta^n$	kg/m ³
Cp_simp	$Cp_{hava} + (Cp_{kati} - Cp_{hava}) * dtopo1.theta^n$	J/(kg·K)

3.7 Geometry

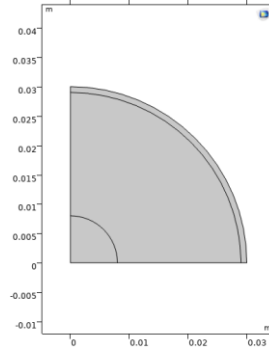


Figure 3. 5: Geometry definition in COMSOL program.

The topology optimization was carried out in two dimensions; therefore, the material was modeled accordingly in 2D. A quarter-circle geometry was created. The reason for modeling only a quarter of the domain is that symmetry boundary conditions will be defined in later stages of the analysis. Inner circle radius is 8mm and outer circle radius is 30mm. Shell thickness defined as 1mm.

3.8 Material Definition

The geometry was previously created, and the inner region corresponds to the heat source. The material of the heat source was selected as aluminum; therefore, the A360 material from COMSOL's material library was assigned to this region. The same material was also assigned to the outer wall. As mentioned earlier, the area between the heat source and the outer wall defines the design domain. Within this domain, a heat sink will be designed through topology optimization, guided by the objective function and subject to the imposed constraints.

For this design region, a blank material was defined. The values for thermal conductivity, heat capacity, and density of this blank material were entered as provided in Table 3.3. These definitions are essential for carrying out the topology optimization process. The material properties are defined as functions of the design variable, in accordance with the optimization formulation previously discussed.

3.9 Topology Optimization

To activate the topology optimization module, the previously defined design domain was selected. In this module, the area to be optimized is specified using the mathematical formulations presented in Section 2.2. The filter type is also selected at this stage. As previously mentioned, filtering is employed in topology optimization to prevent checkerboard patterns. The definition of the Helmholtz filter is carried out in this section. The effect of this parameter on the resulting designs will be examined in later stages of the study. Likewise, the projection type is defined here; however, in this study, the projection type was set to None.

The SIMP method is selected as the material distribution approach and is also defined within this part of the setup. Parameters such as the penalization factor and the minimum penalized volume fraction are specified here as well. The influence of the penalization factor on the design outcomes will be analyzed in the subsequent sections.

In addition to the definitions for the design domain, the density values for the heat source and the outer wall are set to 1 in this section. This indicates to the software that these regions are to remain solid and are excluded from the topology optimization process within the design domain.

3.10 Boundary Conditions

The definition of boundary conditions was carried out in this section, under the Heat Transfer in Solids interface. As previously mentioned, while the aim was to observe the effects over a full circular domain, the design was modeled as a quarter circle. To account for this, symmetry boundary conditions were applied here. The purpose of modeling only a quarter of the domain is to reduce the computation time, as topology optimization analyses can be computationally intensive.

A heat source value was assigned to the designated heat source region, with a total heat rate of 12.5 W. On the outer surface of the wall, external forced convection was applied to simulate a wind flow with a velocity of 0.01 m/s acting on the boundary. Additionally, to represent internal forced convection, an out-of-plane heat flux condition was applied to the design domain. This was done to model airflow

perpendicular to the cross-sectional area of the design region, as described in the Problem Definition section.

Within this definition, parameters such as air temperature and velocity were specified. The velocity of the airflow was set to 25 m/s.

3.11 Mesh

After the definition of boundary conditions, the meshing process was carried out. The heat source, design domain, and outer wall were all meshed. Care was taken to ensure that the mesh element sizes were not too small so as to excessively increase computation time, and not too large so as to compromise the accuracy of the solution.

3.12 Solver

Important definitions were made in the Solver section. Under this section, a dedicated solver for topology optimization is available. Within this solver, the method to be used for solving the optimization problem is selected. In this study, the SIMP method was employed. Additionally, the convergence tolerance and the maximum number of iterations were specified here. The tolerance was set to 0.001, and the maximum number of iterations was set to 100.

The objective function was also defined in this section within the COMSOL environment. The cost function previously described in Equation 2.6 was implemented here. The objective function was set to be minimized. As a constraint, the volume fraction was also defined in this section.

Following the completion of these crucial definitions—each of which plays a significant role in the success of the optimization process—the problem was solved using a stationary solver.

4 RESULTS

After completing all the necessary preliminary steps, the analyses were carried out. In this study, various parameters were altered, and their effects on the design and simulation results were examined. Specifically, the influence of changes in the penalization parameter, filter radius, volume fraction, and inlet velocity on the design outcomes was investigated.

The different designs obtained through these parameter variations were reanalyzed using finite element analysis to ensure the accuracy of the results. This step was necessary because the temperature values directly obtained from the topology optimization solver are not always accurate, mainly due to the presence of gray regions in the material distribution.

To overcome this issue, a post-processing step was applied in which regions with a design density of 0.5 or higher were retained, and these filtered geometries were subjected to a separate finite element analysis. This approach was adopted to ensure that the final results reflect realistic and physically meaningful performance.

Table 4. 1: Parameters used in analysis.

Symbol	Value	Definition
n	3	Penalization Factor
mbmax_kati	2E-4 m	Biggest Mesh Size
mbmin_kati	1E-4 m	Minimum Mesh Size
filtreleme_radyusu	1.50E-04	Filter Radius
hacim_orani	0.5	Volume Fraction
A	3	Penalization Factor
W	2E-4 m	Biggest Mesh Size

The parameters used during the simulations are as shown above. The modified parameters and their respective ranges will be discussed in the following sections under separate headings.

4. 1 Filter Radius

Under this heading, the effects of varying the filter radius on the resulting design are investigated. First, topology optimization studies were carried out using different filter radius values. Following the optimization process, the resulting geometries and objective function values were analyzed. As previously mentioned, the objective function in this study is to be minimized in order to obtain the most efficient design. Therefore, the filter radius value that yields the lowest objective function value can be considered the most optimal in terms of performance.

Subsequently, finite element analyses were performed for each geometry obtained with different filter radius values under the same boundary conditions. The cooling performance of each design was evaluated. It is expected that the filter radius value associated with the lowest objective function will also result in the lowest average temperature.

Additionally, in order to highlight the inaccuracies caused by the gray regions remaining in the topology optimization solution, a comparison will be made between the average temperature values obtained directly from the topology optimization solver and those obtained from the filtered geometry through finite element analysis.

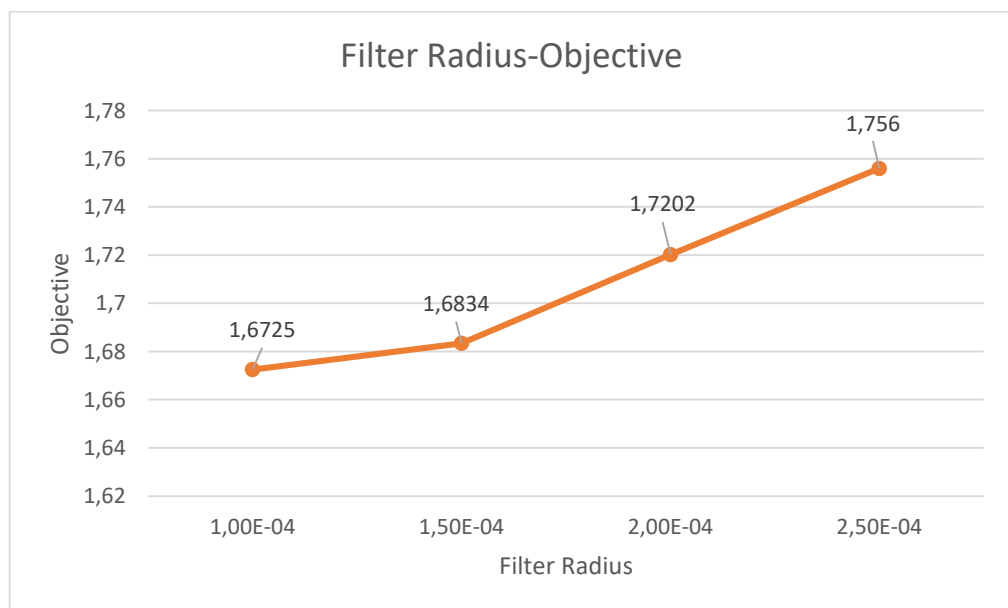
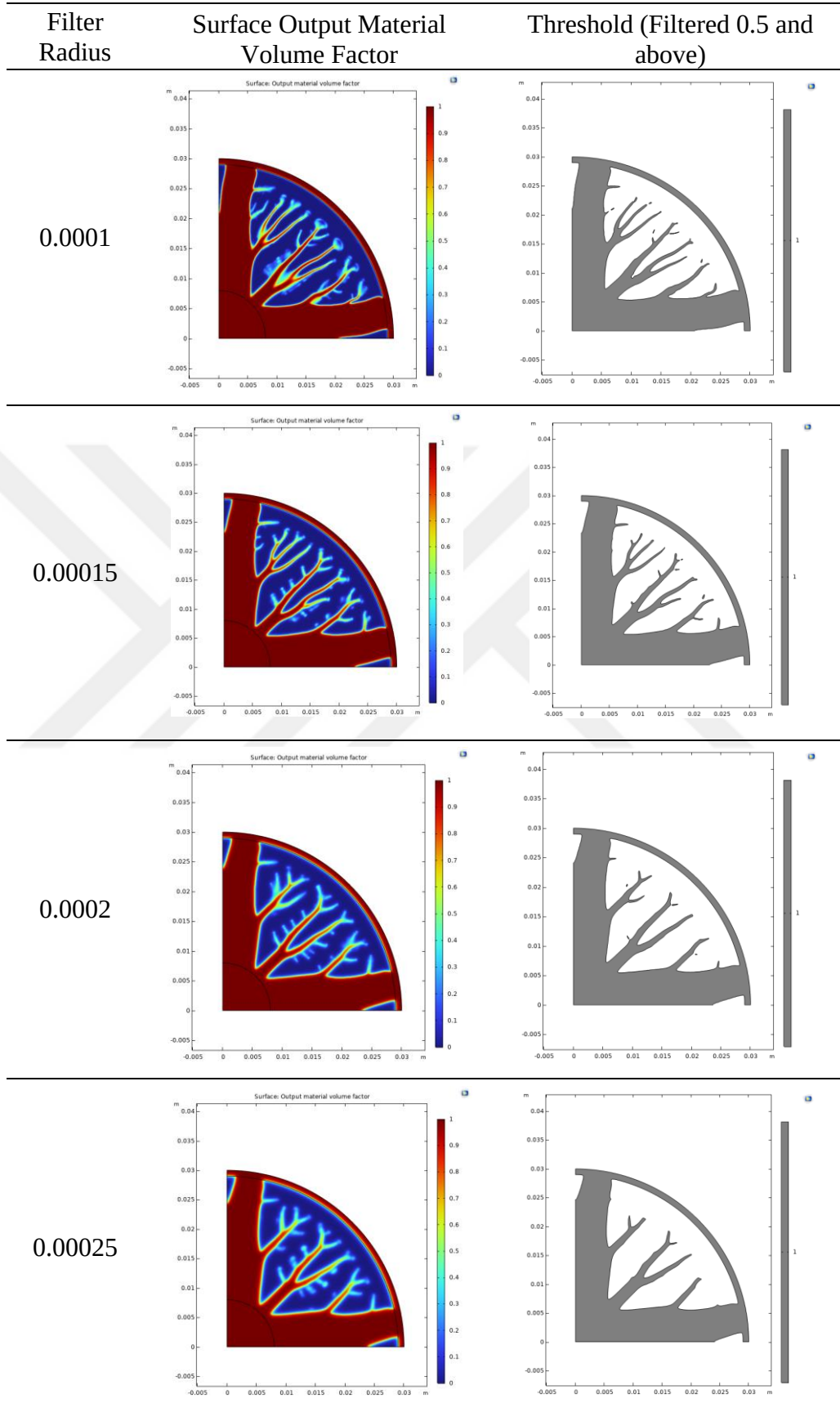


Figure 4. 1: Objective function – filter radius graphic.

Table 4. 2: Geometries obtained for different filter radius values.



As can be seen from the figure 4.1, smaller filter radius values yield better results in line with the defined objective. Since the goal is to minimize the objective function, and it is observed that the objective function value increases as the filter radius increases, it can be concluded that lower filter radius values lead to better performance.

The figures above in Table 4.2 present the geometries obtained from the topology optimization analyses performed with different filter radius values.

As observed from the resulting geometries, smaller filter radius values tend to produce finer and more branched structures. For instance, at a filter radius of 0.0001, the Surface Output Material Volume Factor visualization shows thin, yellow branching patterns around the central thick branch. As the filter radius increases, these fine branches are gradually replaced by thicker, more robust structures. This trend is even more clearly visible in the thresholded geometries.

In the next stage, the filtered threshold geometries were subjected to finite element analysis under the same boundary conditions. The goal here is to determine whether the insights obtained from the objective function are consistent with the physical performance of the designs. It is expected that the lowest filter radius will yield the lowest average and maximum temperature values.

Table 4. 3: Maximum and mean temperature values for different filter radiuses.

Filter Radius	Objective	Definition	Max Temp °C
1.00E-04	1.6725	20.54	20.63
1.50E-04	1.6834	20.57	20.66
2.00E-04	1.7202	20.69	20.78
2.50E-04	1.756	20.75	20.84

The table 4.2 above presents the average and maximum temperature values obtained from the finite element analysis of the filtered geometries. As can be seen, the results are consistent. Filter radius values associated with lower objective function values produced lower temperatures, while average and maximum temperatures increased as the objective function value increased. Although the rate of increase is relatively small and can be considered negligible, it is sufficient to validate the consistency of the results. The limited variation observed here is primarily due to the imposed boundary conditions.

4.2 Volume Fraction

In the previous section, the effect of the filter radius was examined, and a filter radius value of 0.00015 was used in the current analysis. Under this heading, the impact of varying the volume fraction parameter on both the design and the results will be evaluated. This parameter determines the percentage of the design domain that will be occupied by the optimized heat sink. In other words, based on the user-defined volume fraction, the topology optimization process generates the best possible design according to the defined objective function.

This parameter was previously introduced as a constraint in the solver settings. In this study, two volume fraction values—0.2 and 0.5—were investigated. The corresponding objective function values were analyzed, and the resulting geometries were subjected to finite element analysis under the same boundary conditions. Both average and maximum temperature values were recorded. Finally, the consistency between the objective function trends and the thermal performance of the designs was assessed.

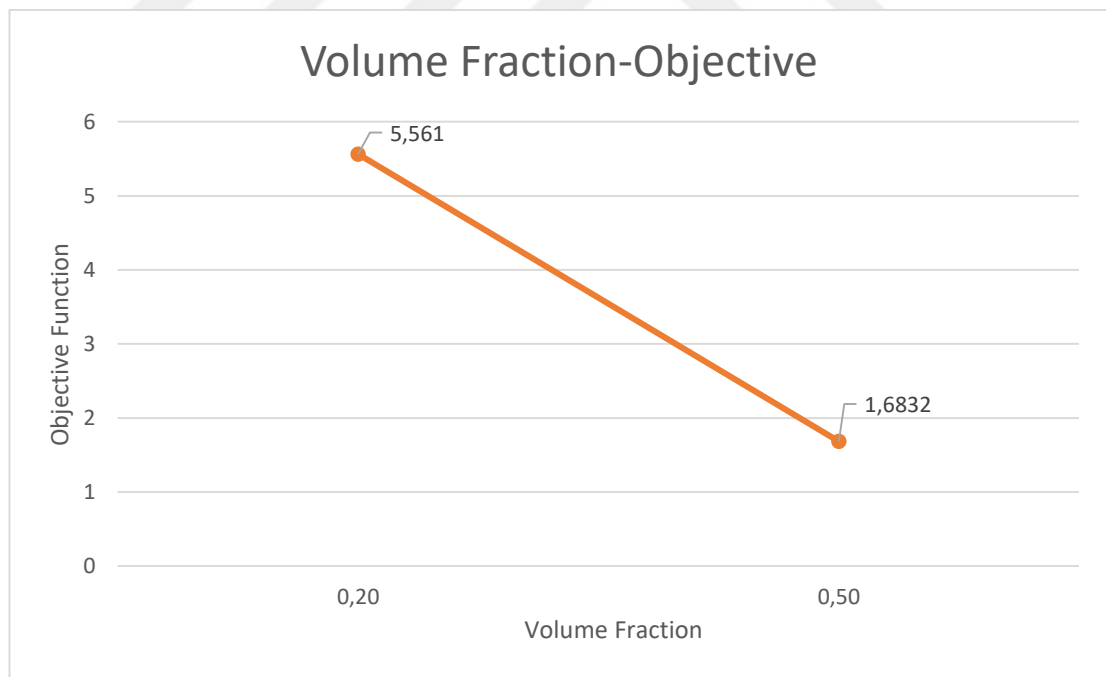
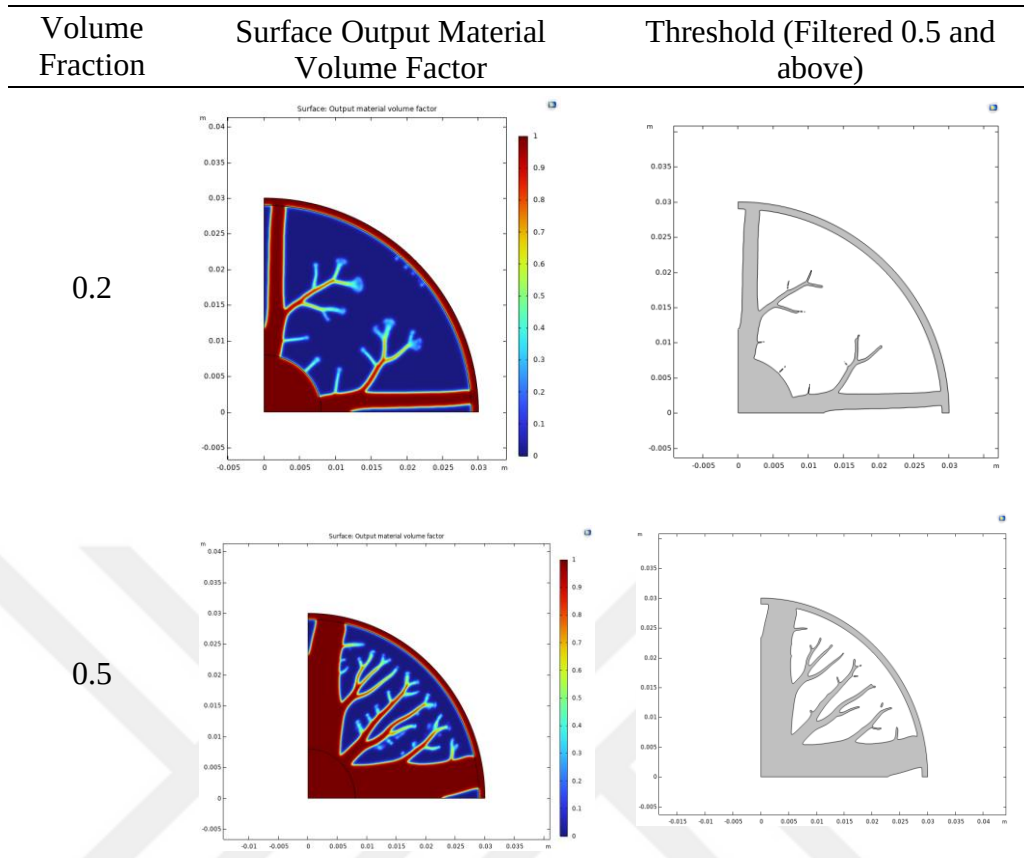


Figure 4. 2: Objective function - volume fraction graphic.

As shown in Figure 4.2 above, the objective function decreases as the volume fraction increases. This indicates that a higher volume fraction is expected to result in improved cooling performance.

Table 4. 4: Geometries obtained for different volume fraction values.



Following this stage, the filtered threshold geometries were subjected to finite element analysis under the same boundary conditions. The results were then evaluated to determine whether they align with the trends observed in the objective function. It is expected that lower objective function values correspond to better cooling performance.

Table 4. 5: Maximum and mean temperature values for different volume fraction.

Volume Fraction	Objective	Mean Temp °C	Max Temp °C
0.20	5.561	20.72	20.92
0.50	1.6832	20.57	20.66

As can be seen from Table 4.5, the trend of the objective function aligns with that of the average and maximum temperatures. The difference is again negligible, which can be attributed to the imposed boundary conditions.

4.3 Penalization Parameter

Under the previous sections, the effects of the filter radius and volume fraction parameters on topology optimization were examined. In the following stages, the filter radius was fixed at 0.00015 and the volume fraction was set to 0.5. In this section, the effects of the penalization coefficient on topology optimization are investigated. This parameter can be seen in Equation 2.7. In order to use the SIMP method, material properties such as thermal conductivity, specific heat capacity, and density were defined as functions of the density variable. These definitions were presented in Table 3.3. The parameter to be analyzed here appears as the exponent of the density variable. The aim is to observe the influence of variations in the penalization parameter on the objective functions. Subsequently, the topology optimization results obtained with these parameters will be subjected to finite element analysis to assess whether they behave consistently with the objective function.

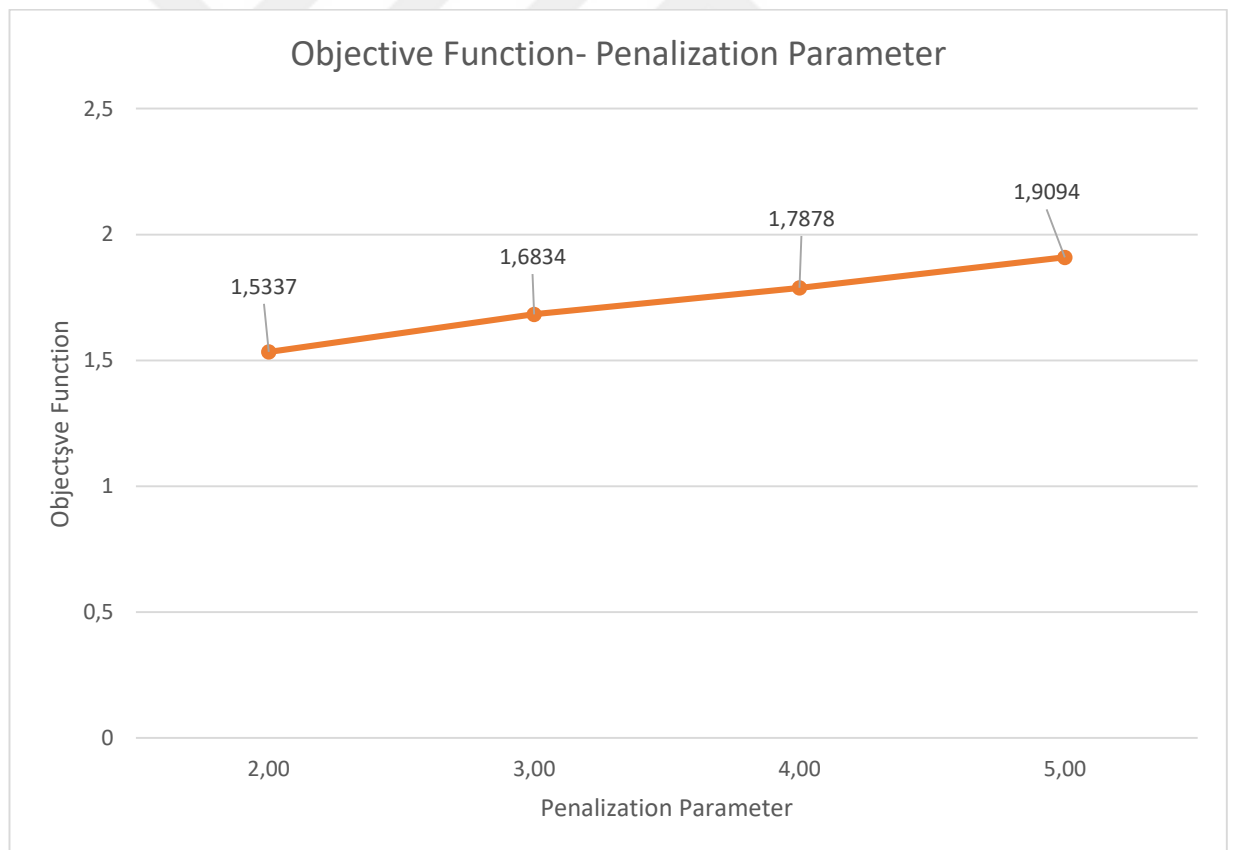


Figure 4. 3: Objective function- penalization parameter.

As shown in Figure 4.3, it is observed that the objective function value increases as the penalization parameter increases. Considering that the goal is to minimize the

objective function, it is expected that among the compared values, a penalization parameter of 2 provides the best cooling performance, while a value of 5 results in the worst performance.

Table 4. 6: Geometries for different penalization parameter.

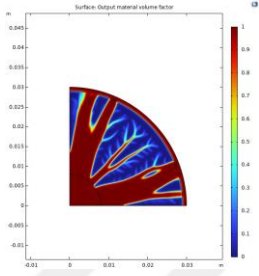
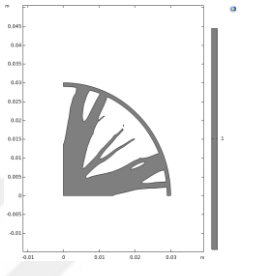
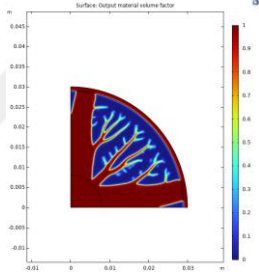
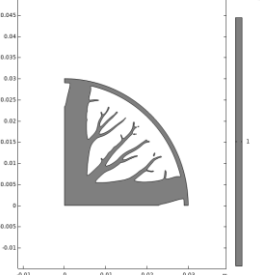
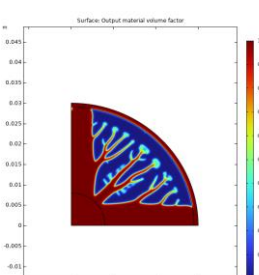
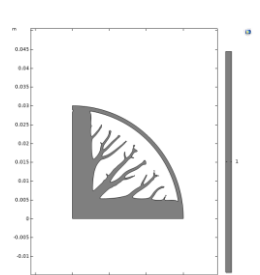
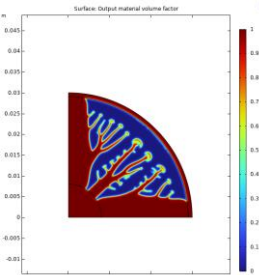
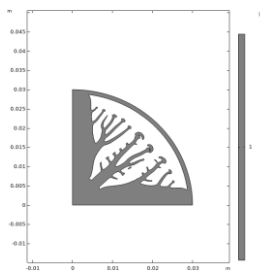
Penalization	Surface Output Material Volume Factor	Threshold (Filtered 0.5 and above)
2		
3		
4		
5		

Table 4.6 presents the results of topology optimization studies conducted with different penalty factors. When the penalty factor is 2, branching is observed around the central structure; however, the adjacent regions do not exhibit similar branching behavior. As the penalty factor increases, both the number and tendency of branch formations increase. For penalty factors of 4 and 5, when the Surface Output Material Volume Factor is examined, yellow structures resembling buds at the tips of the branches begin to appear. Following this stage, the thresholded and filtered designs were subjected to finite element analysis. The average and maximum temperature values were obtained from these analyses.

Table 4. 7: Maximum and mean temperature values for penalization parameter.

Volume Fraction	Objective	Mean Temp K	Max Temp K
2.00	1.5337	293.77	293.86
3.00	1.6834	293.72	293.81
4.00	1.7878	293.71	293.80
5.00	1.9094	293.61	293.71

As a result of the analyses, the values presented above were obtained. In contrast to the other two parameters, in this case, the objective function values did not show a parallel trend with the temperature values. While lower objective function values are typically expected to correspond to lower temperatures, the opposite was observed here. Although the discrepancy is at a negligible level, it nonetheless indicates a lack of consistency.

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BIOGRAPHY

Ismet Can Birinci began his undergraduate studies in Mechanical Engineering at Yildiz Technical University in 2016 and graduated in 2021. During his bachelor's education, he developed an interest in 3D printers and acquired his first printer. He optimized a part using FUSION 360 and manufactured it with his own printer. He participated in the Teknofest rocket and UAV competitions as a member of the GÖK Rocket Team. Although the team was eliminated before the production stages, he gained valuable experience and learned to use CAD software such as CATIA and SOLIDWORKS. He completed his internships at Baykar Defense and Aselsan. He also improved his technical skills through online platforms like Udemy. For his undergraduate capstone project, he designed and produced an on-site balancing machine. Through this project, he used an ARDUINO board to transfer real-time sensor data to MATLAB, where he ran an algorithm to process and analyze the data. The final machine was delivered to Yildiz Technical University. He is currently pursuing a master's degree at Gebze Technical University. Professionally, he began his career as a clerk in the family business and later worked as a sales representative. After two years, he was promoted to sales manager. Since the passing of his father, who was also the company's founder, in 2023, he has continued managing sales operations and currently serves as a board member of the company, Tuzla Civata. He also continues producing custom parts using his six 3D printers.

PUBLICATIONS AND PRESENTATIONS FROM THE THESIS

Birinci I.C., (2025), “Topology Optimization for Heat Transfer Enhancements”, 9st Internaional Hasankeyf Scientific Research And Innovation Congress, Batman, Türkiye 24-26 January

Birinci I.C.,, Önler R., Coşkun F. , “Topology Optimization for Heat Transfer Enhancements”, 5. BİLSEL International Aspendos Scientific Researches Congress June 21-22, 2025 Antalya/ TÜRKİYE

