OPTIMIZING ENERGY EFFICIENCY IN INDUSTRIAL INSTALLATIONS: COMPARISON BETWEEN CONVENTIONAL METHODS AND ADDITIVE TECHNOLOGIES

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Abstract: This paper investigates the improvement of energy efficiency in industrial installations by comparing a conventionally machined cooling channel with an additively manufactured alternative. Numerical simulations combining CFD and FEM were performed to evaluate fluid flow behavior, heat transfer performance and thermal stress distribution for both designs. Results show that the conventional straight channel exhibits limited mixing and uneven temperature distribution, leading to reduced cooling effectiveness. In contrast, the additively manufactured channel, featuring curved geometry and internal enhancements, promotes secondary flow structures that significantly improve heat removal despite a higher pressure drop. Structural analysis confirms that both channels maintain acceptable stress levels under thermal loading. The study demonstrates that additive manufacturing enables geometries that enhance thermal performance and support energy-efficient industrial operation.

Keywords: additive manufacturing, cooling channel design, energy efficiency, CFD–FEM analysis, thermal performance.

1. INTRODUCTION

Energy efficiency has become a central objective in modern industrial engineering, driven by rising operational costs, stricter environmental regulations and the global commitment to reducing carbon emissions. Industrial installations rely on a wide range of mechanical components whose design, material selection and manufacturing methods directly influence the amount of energy consumed during operation. Among these components, thermal management elements such as cooling

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channels, heat exchangers and fluid transport systems play a crucial role in maintaining stable operating conditions and ensuring the longevity of equipment. Inefficient cooling not only increases energy consumption but also accelerates wear, reduces system performance and can lead to unplanned downtime.

Traditionally, cooling channels in industrial equipment have been manufactured using conventional techniques such as drilling, milling or casting. These methods impose significant geometric limitations: channels are often straight, with constant cross-sections, fixed curvature radii and few opportunities for internal optimization. As a result, the thermal performance of conventionally produced channels is frequently constrained by manufacturing feasibility rather than by functional requirements. This mismatch becomes even more pronounced in systems subjected to high thermal loads, fluctuating flow conditions or demanding operational environments [1].

In recent years, additive manufacturing (AM) technologies have transformed the design possibilities for energy-intensive components. Processes such as Selective Laser Melting (SLM) enable the production of complex internal geometries that cannot be achieved through traditional subtractive or formative methods. Cooling channels can be designed with curvature, variable cross-sections, internal lattice structures or topology-optimized pathways that enhance heat transfer and reduce pressure losses [2]. These improvements directly contribute to reducing the energy input required by pumps, compressors or auxiliary cooling systems, thus increasing overall energetic efficiency. The ability to tailor the geometry to thermal and fluid-dynamic constraints opens new opportunities for industrial optimization.

The comparison between conventionally manufactured and additively manufactured cooling components has become a relevant research direction, especially as industries adopt performance-driven design methodologies. Studies have shown that AM-enabled geometries can increase surface-to-volume ratios, promote turbulent micro-mixing, reduce hot-spots and improve coolant flow uniformity [3,4]. However, these benefits must be evaluated in a systematic engineering framework that considers not only thermal performance but also structural integrity, manufacturing cost, reliability, and energy consumption during operation.

A key advantage of AM cooling channels is the possibility to integrate them directly into load-bearing structures or components with complex shapes. This integration reduces the need for external cooling assemblies and lowers parasitic energy losses associated with long piping systems, oversized pumps or inefficient circulation loops. In contrast, conventional cooling layouts often require compromises in performance, leading to increased pumping power or thermal gradients that negatively influence system dynamics.

The finite element method (FEM), combined with computational fluid dynamics (CFD), has become the primary tool for evaluating the performance of cooling channels designed for energy-efficient industrial installations. FEM allows a detailed structural assessment, ensuring that the innovative geometries obtained through AM remain robust under mechanical and thermal loads. CFD simulations, on the other hand, provide insight into flow distribution, temperature fields and pressure drops . Together, these numerical tools make it possible to predict the energy consumption associated with coolant circulation and to identify design configurations that achieve improved efficiency.

The present paper investigates the optimization of energy efficiency in industrial installations through a comparative study of cooling channels manufactured by conventional methods and by additive technologies. The study focuses on the fluid-dynamic and thermal behavior of a standard straight cooling channel and an AM-optimized channel with curved geometry and enhanced internal features. The analysis evaluates pressure loss, heat transfer capability and structural performance using numerical modeling. Through this comparison, the paper demonstrates how additive manufacturing enables significant improvements in cooling efficiency while maintaining mechanical reliability [5,6].

This research aims to provide a methodological framework that supports engineers in selecting appropriate manufacturing strategies for cooling components in energy-intensive applications. By quantifying differences in performance between conventional and additively manufactured cooling channels, the study offers guidance for future industrial implementations, especially in contexts where energy consumption, operational costs and sustainability are critical.

2. METHODOLOGY AND RESULTS

The case study focuses on a cooling channel integrated into an industrial thermal management system, where maintaining controlled temperatures is essential for ensuring stable operation and preventing overheating of critical components. In conventional manufacturing, cooling channels are typically produced through drilling or milling, resulting in straight cylindrical passages with constant cross-sections.

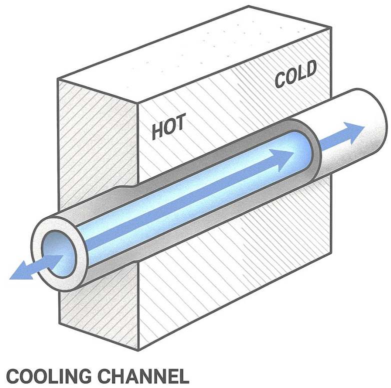

Fig. 1. A cooling channel

These limitations impose constraints on the flow path, restrict the ability to tailor coolant velocity and hinder the optimization of heat transfer. As a result, conventional cooling channels often exhibit uneven temperature distribution, reduced heat removal efficiency, and increased pumping power requirements due to unfavorable fluid-dynamic characteristics.

The reference geometry used in this study is a straight cylindrical cooling channel with a diameter of 10 mm and a length of 150 mm, manufactured through traditional drilling. Its internal surface is smooth, and the geometric simplicity allows predictable flow behavior but limits thermal performance. When subjected to industrial heat loads, such channels often develop hot spots near the downstream region due to insufficient turbulence and restricted heat transfer surface area [7,8].

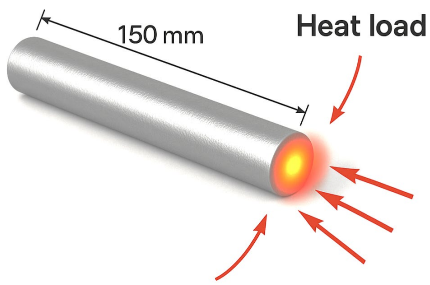

Fig.2. The straight cylindrical cooling channel

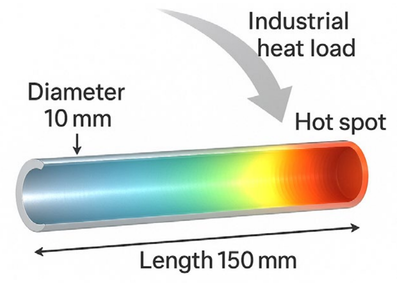

Fig.3. Section on the straight cylindrical cooling channe

In contrast, the additively manufactured variant of the cooling channel is designed to take advantage of geometric freedoms offered by SLM or similar powder-bed fusion technologies. The AM-optimized channel features a curved flow path that follows a sinusoidal trajectory along the same 150 mm length, increasing the effective flow path and promoting localized turbulence.

The internal diameter varies between 8 and 12 mm to control coolant velocity, while internal rib-like features are introduced to enhance mixing and break laminar boundary layers. These design features are impossible or prohibitively expensive to achieve using conventional machining.

Additive manufacturing also enables a more efficient integration of the channel into the surrounding structural component.

The optimized geometry can be embedded closer to heat-generating surfaces, reducing thermal resistance between the hot zone and the coolant. Additionally, the curved layout minimizes stagnation zones and improves thermal uniformity, which contributes to reducing the energy required from the cooling system as a whole.

Material selection for both channel variants is based on industrial stainless steel, commonly used due to its corrosion resistance and thermal stability. The AM version uses a powder formulated for SLM processing, ensuring compatibility with fine geometric features and thin internal walls. Both variants share identical inlet and outlet conditions to allow a fair comparison of fluid-dynamic and thermal performance.

The baseline operating parameters include a water-based coolant circulating at a nominal flow rate corresponding to Reynolds numbers within the transitional regime. This regime is critical because it determines the balance between flow stability and turbulence generation, directly influencing heat transfer and pumping power.

Temperature boundary conditions are applied to simulate a constant heat flux on the outer surface of the channel, reproducing realistic industrial operating scenarios.

The numerical investigation of the two cooling channel configurations—the straight, conventionally machined channel and the additively manufactured curved channel—was carried out through a combined FEM–CFD approach designed to capture both the structural response to thermal loads and the fluid-dynamic characteristics that influence energy consumption. The geometries of the two channels were created as three-dimensional solid models with identical inlet and outlet interfaces, ensuring a directly comparable assessment of their performance. The internal mesh for each model was generated using tetrahedral finite elements, with a higher refinement applied in the curved regions and around the internal features of the additively manufactured channel to accurately resolve velocity gradients and local turbulence. The final meshes consisted of approximately 250,000 elements for the conventional channel and nearly 400,000 elements for the AM variant, reflecting the increased geometric complexity. A mesh-independence study confirmed that further refinement produced variations of less than two percent in the predicted pressure drop and temperature distribution [9,10].

The coolant was modelled as an incompressible Newtonian fluid with constant thermal and rheological properties appropriate for industrial operating temperatures. A uniform inlet velocity was defined to establish a Reynolds number in the transitional regime, while a zero-pressure condition was imposed at the outlet. The channel walls were treated as no-slip surfaces, and a constant external heat flux was applied to represent thermal loading from surrounding equipment. This flow solution produced detailed information about velocity fields, temperature gradients and pressure losses along the channel length. Turbulence was modelled using the SST k–ω formulation, which offers reliable boundary-layer resolution and performs well in curved or recirculating flows characteristic of the AM geometry.

The results of the CFD simulation were subsequently transferred to the structural model to evaluate thermal stresses. Both channels were assigned stainless-steel material properties commonly used in industrial cooling components, and their inlet and outlet faces were constrained to represent fixed mounting within a larger assembly. A coupled thermal–mechanical analysis was performed to assess deformation, von Mises stress distribution and potential points of fatigue. This step was necessary because internal features that improve heat transfer in AM channels may also introduce stress concentrations that require verification.

For the comparison between the two variants, the study examined several performance indicators. These included the pressure drop across the channel, which directly influences the energy required for pumping, and the average heat transfer coefficient, which determines the cooling capacity. Additional attention was given to the wall temperature distribution, the uniformity of heat removal and the structural stress levels under thermal load. By analysing these parameters within a unified numerical framework, the methodology provides a comprehensive basis for evaluating how geometric innovation through additive manufacturing can contribute to enhanced energy efficiency in industrial cooling systems

3. CONCLUSIONS

The numerical simulations revealed clear performance differences between the conventionally machined straight cooling channel and the additively manufactured curved channel. The CFD results show that the straight channel maintains a predictable, largely laminar flow profile along its length, with minimal internal mixing and a relatively uniform velocity field. While this behavior offers stability, it limits the heat transfer capability, resulting in higher wall temperatures, especially toward the downstream section where the thermal boundary layer thickens. The pressure drop across the straight channel remains moderate, but the low level of turbulence restricts its cooling effectiveness and requires a higher coolant flow rate to achieve comparable thermal performances.

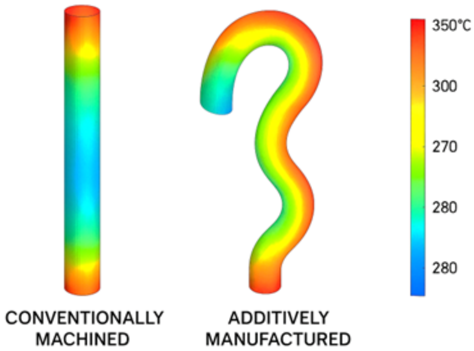

Fig.4. Conventional vs Additive – Heatmap

The image shows a thermal comparison between a cooling channel made using conventional methods and one manufactured with additive technology. The conventional channel, straight and uniform, exhibits a stratified temperature distribution, with hotter zones at the extremities, indicating poor heat dissipation and reduced heat transfer efficiency. In contrast, the additive channel, curved and geometrically optimized, shows a more uniform temperature distribution, reflecting improved internal circulation and superior thermal performance. The color scale on the right illustrates the temperature variation, confirming the advantage of the additive design in preventing heat accumulation.

In contrast, the AM-designed channel demonstrates significantly enhanced fluid-dynamic characteristics.

The curvature of the flow path induces controlled secondary vortices, which increase mixing and disrupt the development of a stable thermal boundary layer. As a result, the temperature distribution along the channel walls becomes more uniform, and the average heat transfer coefficient increases substantially. Local variations in cross-section further contribute to regulating fluid velocity, and regions of higher shear promote faster heat removal.

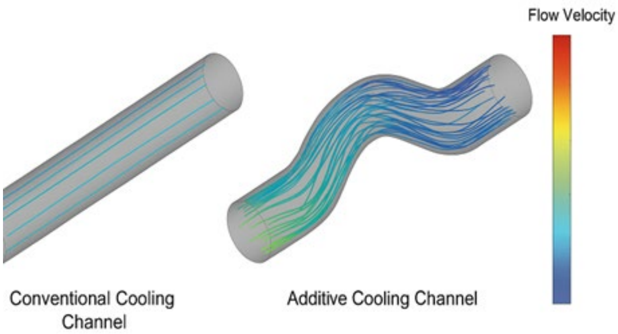

Fig.5. Flow Streamlines

The image presents a comparison of flow lines in two types of cooling channels: a conventional, cylindrical, straight channel and one manufactured using additive technology with a curved and geometrically optimized path. In the conventional channel, the flow lines are straight and parallel, indicating a predominantly laminar regime with limited mixing and heat transfer. In contrast, the additive channel generates wavy, intersecting, and deflected flow lines, signaling the formation of secondary vortices and controlled turbulence that enhance thermal dissipation. The color scale associated with fluid velocity shows that acceleration and deceleration zones are more pronounced in the additive channel, confirming the complexity of fluid–wall interactions and its superior thermal performance.

These mechanisms lead to a measurable reduction in maximum wall temperature despite identical heat flux conditions for both channels.

The price for this improved thermal behavior is a higher pressure drop, generated by the added flow resistance associated with curvature and internal features. However, when evaluating energy efficiency through the ratio of cooling performance to pumping power, the AM channel remains superior, as the thermal gain outweighs the additional pumping effort required.

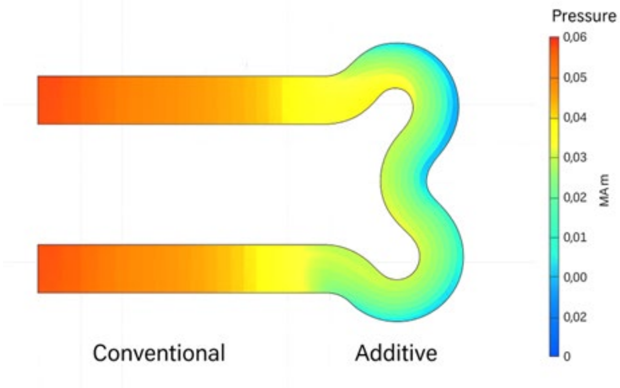

Fig.6. Conventional vs Additive – Pressure Field

The image shows the pressure distribution in two types of cooling channels: a conventional one with a linear geometry and one manufactured using additive technology with a curved path. The conventional channel exhibits a uniformly decreasing pressure gradient, indicating low pressure loss but also a less disturbed flow. In contrast, the additive channel shows pronounced pressure variations along its curves, reflecting intensified interactions between the fluid and the walls and increased hydraulic losses. The color scale on the right illustrates the magnitude of these variations, highlighting that the additive design, although more demanding on the pump, promotes a more complex fluid-dynamic behavior associated with superior thermal efficiency.

The structural analysis confirms that both channels maintain acceptable deformation levels and stress distributions under thermal loading. The conventional channel exhibits a uniform stress pattern with limited gradients, while the AM channel shows localized concentrations near the curved regions and at the transitions between different cross-sections. These stresses remain below material limits and do not compromise structural integrity.

The findings suggest that additive geometries can be reliably integrated into industrial systems, provided that internal features are designed with attention to stress hotspots.

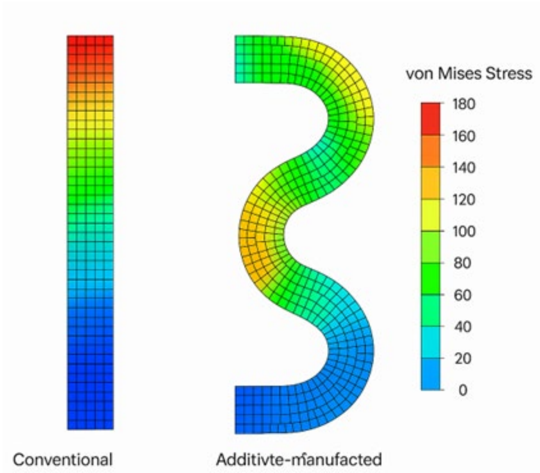

Fig.7. FEM model of the channel with thermal Stresses

The image shows a comparative FEM model of thermal stresses in two types of cooling channels: a conventional, straight, uniform channel and one manufactured using additive technology with a curved and geometrically variable path. The conventional channel exhibits a predominantly uniform von Mises stress distribution, with higher values at the extremities where the thermal gradient is more pronounced. In contrast, the additive channel highlights areas of increased stress in the curved regions, where abrupt changes in direction and variations in wall thickness generate local stress concentrations. The color scale on the right indicates stress levels, demonstrating that while the additive design offers thermal advantages, careful analysis of structural integrity is required at critical points.

Overall, the results demonstrate that additive manufacturing enables a level of geometric refinement that directly contributes to higher cooling efficiency. The curved trajectory, variable cross-section and enhanced mixing features of the AM channel all support improved thermal performance and reduce the energy required to maintain acceptable operating temperatures. Although the increased pressure drop is an inherent consequence of more complex internal flow patterns, it does not negate the efficiency gains achieved by the enhanced heat transfer mechanism. The comparison shows that conventional drilled channels are limited by geometric constraints that inhibit optimization, whereas additive manufacturing offers design freedom that can significantly improve industrial energy performance.

This study highlights the potential of AM-based cooling solutions as viable and advantageous alternatives to traditional methods. The methodology presented here provides a foundation for further research, including experimental validation, fatigue assessment under cyclic thermal loads and integration of topology optimization routines. The findings support the idea that additive manufacturing represents an important pathway toward more efficient, sustainable and high-performance industrial installations.

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