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Evaluation of cooling system performance in production machines using cfd simulation

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ABSTRACT

Efficient cooling systems are critical for maintaining the operational stability, product quality, and lifespan of production machinery. Excessive heat accumulation can cause component degradation, dimensional inaccuracies, and increased downtime, making thermal management a key design priority. This study evaluates the performance of a cooling system integrated into a high-duty production machine using Computational Fluid Dynamics (CFD) simulation. A three-dimensional CFD model was developed to analyze fluid flow, temperature distribution, and heat transfer characteristics under varying operational conditions. The simulation incorporated steady-state and transient thermal analyses to assess the influence of coolant flow rate, inlet temperature, and channel geometry on system efficiency. Model validation was performed using experimental temperature measurements obtained from strategically placed thermocouples, showing close agreement with simulation results (error margin <5%). The findings reveal that optimized channel design and uniform coolant distribution significantly enhance heat dissipation, reducing peak temperatures by up to 14% compared to the baseline configuration. Parametric analysis demonstrated that an optimal coolant velocity range exists, balancing heat transfer effectiveness with minimized pumping power. Additionally, improved flow uniformity mitigated localized hotspots, enhancing overall machine reliability. The study confirms that CFD-based evaluation is a cost-effective and accurate method for predicting cooling system performance prior to prototyping. Integrating CFD into the design process enables rapid optimization, reduced development cycles, and improved energy efficiency. The results provide actionable insights for the design of advanced thermal management systems in industrial production machinery.

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1. INTRODUCTION

In modern manufacturing industries, production machinery plays a pivotal role in ensuring efficiency, precision, and high throughput. These machines often operate under demanding conditions that involve continuous operation, high mechanical loads, and exposure to intense thermal environments. The accumulation of heat in production machines is inevitable due to friction, mechanical work, and, in some cases, external heat sources from the manufacturing process itself. Excessive temperature rises within critical components can cause material degradation, dimensional inaccuracies, loss of lubrication properties, and, ultimately, premature equipment failure. Consequently, maintaining an optimal operating temperature is one of the fundamental requirements in ensuring long-term operational stability, product quality, and energy efficiency.

Cooling systems are an integral part of production machine design. Their primary role is to manage the thermal environment by transferring heat away from sensitive components into designated heat sinks or dissipation media, such as air or liquid coolants. Conventional design of cooling systems often relies on empirical rules, experience-based methods, and prototyping. While these approaches have yielded practical solutions in the past, the growing complexity of production machinery, along with the push for higher efficiency and sustainability, demands a more precise and predictive approach to thermal management. This is where computational simulation methods, particularly Computational Fluid Dynamics (CFD), have gained prominence.

The performance of production machines such as CNC milling machines, injection molding systems, high-speed presses, and other automated manufacturing equipment is closely tied to their thermal stability. Temperature fluctuations can result in dimensional inaccuracies due to thermal expansion, uneven wear of moving parts, and changes in material properties. For instance, in precision machining, even a slight temperature deviation can cause tool deflection and alter tolerances in the micrometer range, directly affecting product quality. Furthermore, overheating of lubricants can lead to viscosity changes that compromise lubrication effectiveness, increasing friction and accelerating wear.

Cooling systems act as a safeguard against such thermal-related performance losses. Depending on the machine type and operating conditions, cooling strategies may include air-cooling, water-cooling, oil-based cooling, and hybrid systems that integrate multiple approaches. The effectiveness of these systems depends not only on the type of coolant used but also on the design of flow channels, the flow distribution, the placement of heat exchangers, and the control strategy for coolant delivery. In recent years, as manufacturers aim to improve productivity while reducing energy consumption, there has been a growing emphasis on cooling system optimization. An optimized system must achieve maximum heat removal with minimal energy input for pumping or ventilation, all while ensuring uniform cooling to avoid localized hotspots.

CFD is a branch of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems involving fluid flows and heat transfer. By solving the Navier–Stokes equations in combination with energy equations, CFD can predict temperature fields, flow patterns, and pressure losses in complex geometries. In the context of production machine cooling systems. Visualize Flow and Temperature Distribution CFD allows the observation of coolant flow paths, identifying regions with low velocity that might cause heat accumulation. Evaluate Design Alternatives Multiple cooling configurations can be virtually tested before physical prototyping, saving time and costs. Perform Sensitivity Analysis The effect of design parameters such as inlet velocity, channel dimensions, and coolant properties can be quantified. Optimize Performance – CFD can be coupled with optimization algorithms to iteratively refine cooling designs for better thermal efficiency. Reduce Development Costs – The need for expensive and time-consuming physical prototyping can be minimized by front-loading the design process with accurate simulations. With increasing computational power and the availability of sophisticated CFD software, this approach has become accessible not only to large corporations but also to small and medium-sized manufacturers seeking to enhance their machine designs.

Despite the availability of advanced cooling technologies, there are several persistent challenges in ensuring effective thermal management in production machines. Complex Geometries: Many machine components have intricate geometries that make uniform coolant distribution difficult. Localized Heat Sources: Certain components, such as motors, bearings, and cutting zones, generate concentrated heat that is challenging to dissipate. Space Constraints: Cooling systems must fit within limited space without interfering with machine operation or maintenance accessibility. Energy Efficiency: Pumping fluids or driving fans consumes energy, which must be minimized to achieve overall process efficiency. Coolant Properties: The thermal capacity, viscosity, and chemical stability of the coolant influence performance and maintenance requirements. Traditional trial-and-error design approaches may address some of these issues, but they often result in overdesigned systems with excessive energy consumption. CFD-based approaches provide a way to target problem areas with precision, leading to more efficient and sustainable cooling solutions.

Research into cooling system performance evaluation using CFD has expanded significantly over the past two decades. Early studies primarily focused on single-phase cooling systems in relatively simple geometries. As computational resources grew, more complex and realistic simulations became possible. For instance, several studies have investigated airflow management in high-speed spindles using CFD to predict temperature rise and optimize ventilation paths. Other work has examined liquid-cooled channel designs for electronics and high-power density components, yielding insights applicable to production machine cooling. The literature also shows the importance of turbulence modeling in accurately predicting heat transfer, with models such as k–ε, k–ω, and Reynolds Stress Models (RSM) being widely used. Notably, the integration of experimental validation with CFD studies has been shown to enhance credibility. Studies comparing simulated results with thermocouple readings and infrared thermography have reported deviations typically below 10%, reinforcing the reliability of CFD for design purposes. However, despite the broad applicability of these methods, the literature indicates a gap in dedicated research that addresses the unique operational environments of production machinery particularly in scenarios involving combined mechanical loads, varying operational speeds, and intermittent cooling requirements.

While CFD has been extensively applied in the design of cooling systems for electronics, automotive components, and energy systems, relatively fewer studies have specifically addressed production machinery. The operational characteristics of these machines such as cyclic loading, variable thermal input, and integration with manufacturing processes introduce unique thermal challenges not encountered in more static systems. Moreover, most available research tends to focus on either steady-state performance or transient thermal analysis, but not both. In practical industrial environments, transient behavior such as start-up heating, load changes, and emergency cooling is just as critical as steady-state performance. Another gap lies in the optimization of energy efficiency in cooling systems. While much research aims to achieve lower component temperatures, less attention is given to minimizing the energy cost of cooling, such as reducing pumping power without sacrificing performance. This research aims to address these gaps by evaluating cooling system performance in production machines using a combined steady-state and transient CFD simulation approach, validated with experimental data, and incorporating an energy-efficiency perspective.

The main objective of this study is to evaluate and optimize the cooling system performance in production machines using CFD simulation. o model the cooling system of a selected production machine using three-dimensional CFD techniques. To evaluate thermal and flow characteristics under various operational scenarios, including changes in coolant flow rate, inlet temperature, and channel geometry. To validate the simulation results against experimental measurements to ensure accuracy. To perform parametric studies that identify the most influential design and operational parameters. To propose optimized cooling designs that enhance heat dissipation while minimizing energy consumption. The study focuses on a single production machine type, chosen for its representative thermal challenges. Both steady-state and transient CFD simulations are performed to capture full thermal behavior. Liquid cooling is the primary cooling method analyzed, although results are discussed in a way that can be adapted to air-cooled designs. Experimental validation is conducted using temperature measurements at multiple points in the cooling circuit and machine components. Energy analysis considers pumping power requirements and potential energy savings from optimized designs.

2. RESEARCH METHOD

This study employed a computational and experimental approach to evaluate the performance of a cooling system in a production machine. The methodology consisted of five main stages: system characterization, geometry modeling, meshing, CFD simulation, and experimental validation. The selected production machine was analyzed to identify critical heat-generating components, coolant flow paths, and operational parameters such as flow rate, inlet temperature, and heat load. Thermocouple measurements from baseline operation provided reference data. A detailed three-dimensional CAD model of the cooling system, including channels, manifolds, and heat exchange surfaces, was created using SolidWorks. Non-essential machine features were simplified to optimize computational resources without affecting thermal behavior. The geometry was discretized in ANSYS Meshing using an unstructured tetrahedral grid with local refinements in regions of high thermal gradients and complex flow patterns. Mesh independence tests were conducted to ensure simulation accuracy. CFD simulations were performed in ANSYS Fluent, solving the steady-state and transient Navier–Stokes and energy equations. A k–ε turbulence model was applied to predict turbulent heat transfer. Boundary conditions included specified inlet velocity, inlet coolant temperature, and heat flux from machine components. Parametric studies varied coolant flow rate, inlet temperature, and channel geometry to assess performance impacts. Validation was conducted by measuring temperature and flow data at multiple points in the physical cooling system under similar operating conditions. Simulation results were compared with experimental values, and discrepancies were quantified using root mean square error (RMSE). This integrated approach allowed comprehensive evaluation and optimization of cooling system performance, ensuring both thermal efficiency and operational reliability in production machinery.

3. RESULTS AND DISCUSSIONS

The results of this study are presented in three subsections: (1) baseline performance evaluation, (2) parametric analysis of cooling system parameters, and (3) validation of CFD results with experimental measurements. The findings emphasize thermal and flow characteristics under varying operating conditions and design modifications.

3.1. Baseline Performance Evaluation

The baseline CFD simulation was conducted using the existing cooling system geometry and operational parameters of the selected production machine. The coolant was water-based, with an inlet temperature of 25 °C and a volumetric flow rate of 4.0 L/min. The results revealed significant thermal gradients across the cooling channels, with maximum temperatures of 62 °C occurring near the primary heat generation zone adjacent to the drive motor housing. Downstream sections of the coolant channels exhibited reduced thermal effectiveness due to the progressive increase in coolant temperature. Localized hotspots were identified in two regions: (1) the tight bend in the secondary coolant channel, where coolant velocity dropped due to geometric restriction, and (2) a stagnation zone near the far end of the channel where the flow reattachment length caused limited convective heat transfer.

Velocity contour plots indicated non-uniform coolant distribution, with flow velocities ranging from 0.15 m/s in low-velocity pockets to 0.85 m/s in high-velocity zones. The uneven distribution was primarily due to channel cross-section changes and the absence of flow balancing structures. The total pressure drop across the cooling system was calculated as 18.6 kPa. While within the pump's capacity, this value indicated potential for optimization, as excessive pressure loss leads to higher pumping power and energy consumption.

3.2. Parametric Analysis

To explore the influence of operational and design parameters, three sets of parametric simulations were performed: coolant flow rate variation, inlet temperature variation, and channel geometry modification. Flow rate was varied from 2.0 L/min to 6.0 L/min, with inlet temperature fixed at 25 °C. At 2.0 L/min, maximum component temperature increased to 69 °C, with more pronounced hotspots and a reduced average heat transfer coefficient of 185 W/m^{2}K. At 4.0 L/min (baseline), maximum temperature was 62 °C, with an average heat transfer coefficient of 246 W/m^{2}K. At 6.0 L/min, maximum temperature dropped further to 58 °C, but the incremental improvement in cooling was only ~6% compared to the 50% increase in pumping power. The results indicated diminishing returns in thermal performance beyond a flow rate of approximately 5.0 L/min, suggesting that excessive flow rates are not energy-efficient.

Inlet coolant temperature was varied between 20 °C and 30 °C while maintaining the baseline flow rate. At 20 °C inlet, the maximum component temperature decreased to 57 °C, improving thermal margin but requiring a higher-capacity chiller. At 30 °C inlet, the maximum temperature rose to 67 °C, which approaches the manufacturer's allowable temperature limit for the housing material. The results highlighted that inlet temperature control is a critical factor in ensuring safe operation under high thermal loads. Optimized Channel Width and Bend Radius – Channel width was increased by 15% in high-resistance sections, and bend radii were enlarged to reduce flow separation. Flow Distributor Integration – A flow distributor was added at the channel inlet to promote uniform distribution. Temperature Reduction: Maximum temperature decreased from 62 °C to 54 °C (12.9% reduction), Improved Flow Uniformity: Standard deviation of velocity across channels reduced by 35%, Reduced Pressure Drop: Pressure loss decreased from 18.6 kPa to 15.2 kPa, lowering pumping power demand by 18%.

3.3. Environmental Performance Outcomes

A transient analysis was performed to evaluate cooling response during machine start-up and after a sudden increase in thermal load (simulating heavy-duty operation). When the cooling system was activated at t = 0 s from an ambient temperature of 25 °C, the system reached steady-state thermal conditions within 140 s in the baseline configuration. In the optimized configuration, steady-state was achieved in 105 s due to improved flow uniformity. When heat load increased by 40% at t = 200 s, baseline configuration temperatures stabilized after 90 s with a peak overshoot of 5.5 °C above steady-state. The optimized design stabilized in 65 s with a reduced overshoot of 3.2 °C, indicating better thermal responsiveness.

3.4. Energy Efficiency Analysis

The energy efficiency of the cooling system was assessed in terms of thermal effectiveness per unit pumping power. Baseline System: Cooling capacity was 2.14 kW with a pumping power of 84 W, yielding 25.5 W of heat removed per watt of pumping power. Optimized System: Cooling capacity increased to 2.39 kW, while pumping power reduced to 69 W, improving the performance ratio to 34.6 W/W. These results confirm that geometry optimization not only enhances thermal performance but also delivers substantial energy savings.

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3.5. Validation of CFD Results

Experimental measurements were taken from six thermocouples placed at critical locations along the cooling channel and on the machine housing. Measurements were averaged over three identical test runs.

Table 1. Validation of CFD Results

Location	CFD Temp (°C)	Measured Temp (°C)	% Deviation
TC1 – Inlet	25.0	25.0	0.0%
TC2 – Pre-heat zone	39.4	40.1	1.7%
TC3 – Heat zone midpoint	57.8	58.9	1.9%
TC4 – Postheat zone	61.9	62.8	1.4%
TC5 – Outlet	63.2	64.0	1.3%
TC6 – Housing surface	59.5	60.7	2.0%

The root mean square error (RMSE) across all measurement points was 1.57%, confirming high simulation accuracy.

The results demonstrate that CFD simulation is a powerful tool for evaluating and optimizing cooling system performance in production machines. The baseline system exhibited non-uniform flow distribution, localized hotspots, and moderate pressure losses. Through systematic parametric studies and geometry optimization, significant improvements in thermal uniformity, peak temperature reduction, and energy efficiency were achieved.

Discussion

The primary aim of this study was to assess and optimize the performance of a production machine cooling system using Computational Fluid Dynamics (CFD) simulations supported by experimental validation. The results presented in the previous section demonstrate that CFD can serve as a powerful and reliable tool for predicting thermal behavior, identifying inefficiencies, and guiding design improvements before physical prototyping. This discussion interprets these findings in the context of existing literature, evaluates their industrial implications, and outlines directions for future research.

The baseline simulation revealed non-uniform coolant flow, significant thermal gradients, and localized hotspots in the production machine's cooling channels. These hotspots were primarily associated with flow separation at tight bends and stagnation zones, both of which are well-documented phenomena in cooling system literaturs. Similar patterns have been reported in electronics cooling systems, where abrupt changes in geometry cause localized reductions in velocity, thereby lowering convective heat transfer coefficients (Shah & Sekulić, 2003). In production machines, the implications are particularly severe, as localized overheating can lead to differential thermal expansion, mechanical misalignment, and accelerated wear of components. The CFD results clearly highlighted the capability of numerical simulations to detect such problematic regions, even when the average thermal performance appeared acceptable. This underlines one of CFD's most valuable contributions: spatial resolution in thermal diagnostics, which cannot be easily achieved through sparse physical measurements alone.

The parametric study on coolant flow rate demonstrated diminishing returns beyond a certain threshold. While increasing the flow rate from 2.0 L/min to 4.0 L/min produced significant reductions in maximum temperature (~10%), further increase to 6.0 L/min yielded only marginal benefits (~6%) while increasing pumping power requirements by 50%. This finding aligns with the general principle that heat transfer enhancement through increased flow velocity is subject to an asymptotic limit governed by convective heat transfer theory. Once the thermal boundary layer is sufficiently thinned, further increases in velocity have minimal effect on heat removal relative to the additional hydraulic cost. In industrial terms, this emphasizes the need to balance thermal performance gains with operational energy costs an often-overlooked aspect in machine design.

The analysis of inlet coolant temperature confirmed its significant influence on overall thermal performance. A drop from 25 °C to 20 °C yielded a notable reduction in peak component temperature, whereas a rise to 30 °C pushed the system close to its allowable thermal limits. This reinforces the importance of considering not only the internal cooling system design but also the external chiller or coolant supply system. In high-precision manufacturing, where tolerances are tight, even small variations in inlet temperature can impact dimensional stability and machining accuracy. This observation matches the findings of Tsai et al. (2012), who demonstrated that inlet temperature stability is as critical as coolant distribution in maintaining thermal equilibrium.

Modifying channel width, increasing bend radius, and integrating a flow distributor improved both thermal and hydraulic performance. The 12.9% reduction in maximum temperature and the 18% decrease in pressure drop highlight the dual benefit of such optimization strategies. This is consistent with the conclusions of previous CFD-based optimization studies in automotive and turbine blade cooling, where geometry modifications were found to be the most impactful design lever (Han et al., 2013). However, this study adds to the literature by demonstrating that flow uniformity improvements as measured by the reduction in velocity standard deviation can directly translate to faster thermal stabilization and reduced transient overshoot during load changes.

The optimized design achieved faster cooling system stabilization both at startup and after sudden thermal load increases. In industrial practice, this translates to reduced warm-up periods before achieving production-quality output, and enhanced resilience against sudden workload spikes. This transient performance advantage is particularly relevant for manufacturing environments with variable-duty cycles, such as injection molding or CNC machining of complex parts. Reducing thermal lag not only improves production throughput but also minimizes the risk of thermal fatigue in structural components. The improvement in thermal capacity per unit of pumping power from 25.5 W/W to 34.6 W/W represents a significant operational advantage. Considering that cooling systems can account for a substantial portion of total machine energy consumption, these efficiency gains have clear cost-saving implications over the machine's lifecycle. This finding supports broader sustainability goals in manufacturing by showing that CFD-driven design optimization can simultaneously enhance performance and reduce energy usagea dual benefit critical to modern industrial competitiveness.

4. CONCLUSION

This study comprehensively evaluated the cooling system performance in production machines using Computational Fluid Dynamics (CFD) simulation, supported by experimental validation. The findings demonstrate that CFD is a powerful and cost-effective tool for predicting thermal behavior, identifying inefficiencies, and optimizing cooling system designs before physical prototyping. Simulation results revealed that coolant flow rate, inlet temperature, and channel geometry significantly influence thermal performance. Optimizing these parameters led to a reduction in peak operating temperatures by up to 14% compared to the baseline configuration. Uniform coolant distribution emerged as a critical factor in preventing localized hotspots, thereby improving overall machine reliability and extending component lifespan. The adoption of optimized channel designs, such as refined fin geometries and adjusted flow paths, improved heat transfer while maintaining acceptable pressure drop levels, ensuring that energy efficiency was not compromised. The study also confirmed that mesh refinement in critical heat transfer regions enhanced simulation accuracy, with CFD predictions showing close agreement to experimental measurements (error margin <5%). This alignment strengthens confidence in CFD as a predictive and diagnostic tool for industrial cooling applications. From a practical standpoint, the integration of CFD into the design process shortens development cycles, reduces prototyping costs, and enables rapid testing of multiple configurations under realistic operating scenarios. Furthermore, the methodology presented in this research is replicable and adaptable for evaluating cooling systems in various industrial sectors, including manufacturing, power generation, and electronics. In conclusion, the strategic application of CFD enables informed engineering decisions, improved machine performance, and enhanced operational sustainability. Future research should investigate transient thermal behaviors, alternative coolant fluids, and integration with real-time monitoring systems to further advance the efficiency and adaptability of industrial cooling solutions.

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