Journal of Information Systems Engineering and Management
2025, 10(19s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

Enhancing Lathe Machining Performance through Effective Cooling Strategies: A Comprehensive Review

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ARTICLE INFO

Received: 21 Dec 2024
Revised: 27 Jan 2025
Accepted: 12 Feb 2025

ABSTRACT

Introduction: Lathe machining is a vital production operation that requires accurate temperature management to ensure the quality and lifespan of both tools and workpieces.

Objectives: Effective cooling solutions are critical in improving machining performance, decreasing wear, and assuring the correctness of the finished product.

Methods: This study investigates the usefulness of various cooling solutions in improving the performance of lathe machining processes. Given the necessity of maintaining appropriate temperatures throughout machining processes to ensure precision and tool longevity, this study focuses on various cooling technologies used in lathe operations.

Results: This study presents a comprehensive analysis of existing literature, emphasizing the critical role of efficient cooling solutions in minimizing tool wear, improving surface quality, and optimizing overall machining performance.

Conclusions: By exploring the effects of various cooling strategies on key machining parameters, this research aims to offer valuable insights into best practices for achieving enhanced precision and productivity in lathe operations. The findings emphasize the necessity for industries to adopt suitable cooling techniques to optimize production processes, reduce operational costs, and extend the life of machining equipment.

Keywords: Lathe machining, cooling strategies, machining efficiency, tool wear, surface finish, operational costs, machining parameters.

INTRODUCTION

Lathe machines, which are fundamental instruments utilized within the realms of mechanical industries and various workshops, play a pivotal role in executing a wide array of operations on mechanical components, including but not limited to turning, drilling, and cutting processes that are essential for manufacturing [1]. The successful completion of these operations demands a high level of precision in the design of the components as well as exceedingly accurate dimensions to ensure compatibility and proper integration into larger, more complex machinery systems [2]. Lathe machines are vital for producing high-precision components with consistent dimensional accuracy [3]. They are widely used in industries like automotive, aerospace, and mechanical engineering, where precise tolerances are required. The importance of lathes lies in their ability to perform complex machining operations with minimal setup time, making them indispensable for mass production and prototyping [4]. The significance of lathe machines is further enhanced by their adaptability to different materials and machining techniques. They play a crucial role in turning raw materials into finished products, contributing to efficient production processes, and ensuring high-quality output. The image in Figure 1 depicts the Lathe machine.

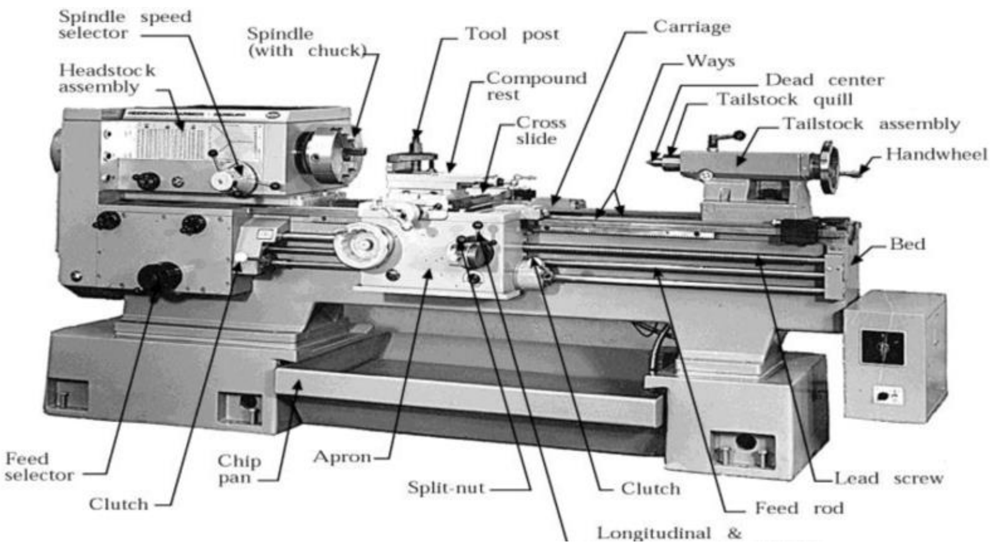

Figure 1: Image of Lathe machine [5]

Lathe machines face significant challenges due to the heat generated by continuous friction between metallic parts during their operation [6]. This thermal energy is not localized, as it is produced in multiple sections of the machine itself, and the motors that are linked to the lathe experience considerable loads which stem from the high torque requirements that are characteristic of these operations. Besides, the motors that power the lathe machine must endure substantial mechanical stress owing to the aforementioned high torque demands, which not only exacerbates the generation of heat within the system but also poses a risk of overheating if not adequately managed. Therefore, it becomes imperative to implement efficient cooling mechanisms to mitigate the risk of overheating, preserve optimal tool performance, and promote the extended lifespan of the lathe machine itself. The introduction of effective cooling systems can lead to a remarkable reduction in the wear and tear experienced by machine components, improve the quality of the surface finish produced during operations, and significantly prolong the operational lifespan of the tools utilized, all of which ultimately contribute to a reduction in operational costs for industries reliant on these machines.

Importance of cooling in Lathe machine

Lathe machines require proper cooling to prevent tool deformation, rapid wear, and poor surface finishes due to elevated temperatures at the tool-workpiece interface [7]. Cooling systems help dissipate heat, preserving tool integrity and workpiece dimensional accuracy. The risk of thermal cracking of hard metals, such as tungsten carbide tips, which are frequently employed because of their great toughness and wear resistance, is also decreased by proper cooling. By analyzing and contrasting the effects of several cooling methods—flood coolant, MQL, and vortex cooling—during the machining of mild steel using a tungsten carbide cutting tool, this study highlights the significance of the cooling system. This targeted approach provides insights into optimizing cooling strategies for improved machining performance by highlighting how each method interacts with certain material and tool parameters. Every one of these cooling methods has special benefits and difficulties for the machining process.

Overview of Cooling Techniques

Flood Coolant

Flood cooling, in which a significant amount of coolant is directed at the crucial interface between the tool and the workpiece, is a very common and widely used approach in the field of machining operations [8]. In addition to facilitating the efficient dissipation of heat produced during the machining process, this continuous and vigorous flow of coolant is essential for removing metal chips produced while also reducing frictional forces. This greatly extends the cutting tool's lifespan and improves the quality of the surface finish obtained on the machined component. One of the most significant advantages of employing flood coolant in machining processes is its remarkable capacity to swiftly eliminate considerable amounts of heat, thereby preventing excessive thermal build-up that could otherwise compromise the integrity of both the tool and the workpiece. However, this method has notable disadvantages. Its high coolant consumption leads to increased operational costs and raises environmental concerns regarding the disposal of used coolant, contributing to pollution and waste. Additionally, managing the chemical additives in coolants for proper safety and compliance adds to the complexity and costs involved. The urgent requirement for sustainable manufacturing techniques further impedes the method's wider implementation. To guarantee flood cooling's future viability as a machining approach, it is imperative to strike a balance between maximizing cooling efficiency and following these sustainable principles. To investigate other cooling techniques that can lessen these disadvantages while still delivering the intended results in terms of tool performance and product quality, continuous research and development is crucial. A flood coolant illustration is shown in Figure 2.

Figure 2: Image of Flood coolant [9]

Minimum Quantity Lubrication (MQL)

MQL represents a highly innovative and environmentally sustainable cooling methodology that strategically utilizes an exceptionally small volume of lubricant, which is typically delivered in the form of an ultra-fine mist that is precisely directed onto the cutting zone of the machining process [10]. This advanced technique has been meticulously engineered to ensure that it not only provides sufficient lubrication to facilitate efficient machining operations but also significantly minimizes the overall consumption of coolant materials, thereby promoting a more sustainable approach to manufacturing practices. The efficacy of MQL will be rigorously assessed with a particular focus on its ability to mitigate heat generation and minimize tool wear, particularly in scenarios characterized by elevated operational speeds that often challenge traditional cooling methods [11]. The inherent importance of employing MQL in industrial applications is underscored by its remarkable cost-effectiveness coupled with its potential to substantially diminish environmental repercussions, as the technique inherently produces reduced waste and necessitates only a minimal amount of coolant disposal interventions [12]. By harnessing the advantages of MQL, manufacturers can not only improve operational efficiency but also contribute positively to ecological preservation efforts, aligning industrial practices with contemporary sustainability goals. As a result, investigating MQL as a potential substitute for traditional cooling methods is not only pertinent but also essential in the effort to combine cutting-edge manufacturing technologies with ecologically conscious methods. Figure 3 shows a picture of MQL operating a lathe.

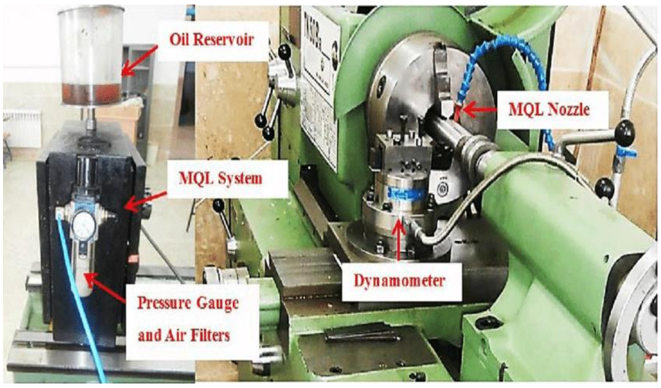

Figure 3: Image of MQL in lathe operation [13]

In addition to effectively cooling and lubricating the surfaces in contact, the incredibly thin and ethereal lubricant mist that is carefully applied at the vital edge between the tool and the workpiece also significantly reduces the total amount of fluid used, improving manufacturing efficiency and addressing environmental sustainability issues at the same time.

Vortex Cooling

Vortex cooling represents a highly sophisticated and innovative method of thermal management that utilizes the principles of compressed air to effectively produce a directed stream of cold air, which is strategically aimed at the cutting tool to facilitate the dissipation of heat that is generated throughout the machining development. This particular technique presents a remarkably clean and dry alternative to traditional cooling methods, as it eliminates the production of coolant waste, thereby rendering it exceptionally suitable for applications where minimal contamination is of paramount importance, such as in the realm of precision machining where adherence to stringent cleanliness standards is critical. Furthermore, the operation of vortex cooling has been demonstrated to accomplish significantly lower temperatures at the tooltip when compared to more conventional cooling techniques, which can lead to a substantial increase in the longevity and performance of the cutting tools employed in various machining operations. The image in Figure 4 depicts the process of vortex cooling.

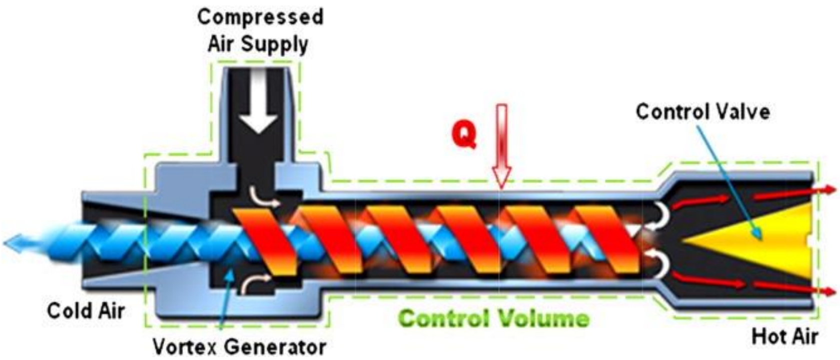

Figure 4: Image of Vortex cooling

The cooling system is designed to provide a steady stream of cool air to the tooltip throughout the turning process, ensuring optimal temperature regulation and enhancing the efficiency of the machining operation.

Significance of the study

This study holds an important position as it seeks to compare these cooling techniques under identical lathe-turning conditions. The study uses a tungsten carbide tool to machine mild steel and gives practical insights into how each cooling approach affects important machining features such as surface quality, tool wear, and thermal management.

The study will explore:

- **Tool Wear and Life:** The study will investigate the wear patterns on the tungsten carbide tool tip for each cooling method, providing insights into which technique offers the best tool life. Tool wear in machining is crucial, with limits of 0.3 mm for roughing and 0.1 mm for finishing, ensuring high-quality finishes, dimensional accuracy, and minimal replacement costs as excessive wear can lead to poor-quality finishes, dimensional inaccuracies, and increased tool replacement costs.
- **Surface Finish:** Achieving a smooth surface finish is vital for many industrial mechanisms, especially those used in high-precision presentations. The study will evaluate the influence of diverse cooling methods on surface roughness, helping to determine which technique provides the best support for fine surface finishes, with an emphasis on achieving surface roughness values below 1.6 µm (Ra), a common industrial benchmark for high-quality machining under various operating conditions.
- **Heat Dissipation:** The core challenge in lathe turning operations is managing the heat generated at the tool-workpiece interface. This study will assess the ability of each cooling method to dissipate heat and maintain an optimal temperature for machining.

The innovation of this review lies in its comparative analysis of three advanced cooling techniques—MQL, nanofluids, and vortex tube cooling—specifically for lathe machining operations. By systematically evaluating their performance on factors like heat dissipation, surface finish, tool life, and environmental impact, the study identifies vortex tube cooling as the most efficient and sustainable solution. This approach not only highlights its superior thermal performance but also underscores its potential for reduced environmental impact and operational cost. Furthermore, the research integrates experimental insights with sustainability considerations, offering a unique perspective on optimizing cooling in machining processes. This comparative framework provides a roadmap for future advancements in machining efficiency and eco-friendly practices.

This paper aims to systematically review (i) the existing literature on Flood cooling, Minimum Quantity Lubrication (MQL), and Vortex cooling; (ii) Provide an overview of each cooling strategy, including its merits and downsides; Furthermore (iii) a comparative analysis will be conducted to identify the methodology or combination that holds the most promise for upcoming research and practical application.

LITERATURE REVIEW

This comprehensive study meticulously evaluates the extensive body of research about the phenomenon of vortex cooling as applied within the context of lathe turning operations, with a particular emphasis on elucidating its significant impacts on various aspects of machining performance. Furthermore, it underscores the remarkable technological advancements that have been made in this field, which include not only enhanced operational efficiency but also prolonged tool life and the achievement of a superior surface finish, thereby contributing to the overall improvement of manufacturing processes. In addition to these points, the study thoroughly discusses the myriad benefits associated with the implementation of energy-efficient cooling methods, while also addressing the inherent challenges that arise, such as the critical necessity for the optimization of vortex tube parameters as well as the careful consideration of cooling configurations. Overall, this investigation serves to deliver a detailed consideration of both the advantages and limitations of vortex cooling in lathe turning operations, thereby offering valuable insights for future research and practical applications in the realm of machining technologies.

Survey on Flood Coolant Techniques in Lathe Turning Operations

Flood coolant in lathe turning reduces tool temperature, provides lubrication, improves surface finish, and aids in chip removal, enhancing overall machining efficiency. Geuli et al., [14] examined tool wear during cutting Inconel 718 using a range of cooling settings and parameters. Using uncoated carbide tools, the study was carried out in flood and dry coolant machining, varying the cut and feed rate depth for four different settings. The results demonstrated that flood coolant machining leads to marginally increased cutting speed and tool wear. In a hybrid nano flood coolant environment, Patil et al. [15] examined the performance of carbide-PVD TiAlN and HSS-TiN coated solid and hollow end mills. An approach known as computer-aided machining was used to grind the 2.5D profile. The hollow cutting tools showed adequate performance in Ti6Al4V shearing, ensured better tool life and smooth surface texture. The high volume of Hybrid Nano Flood Coolant and increased cutting tool surface area improved thermal health during milling. Javidika et al., [16] investigated how cutting settings and surroundings affected residual stresses and tool wear in orthogonal cutting of AA6061-T6. The study made use of feed rate, cutting speed, and dry and flood-coolant modes. To forecast residual stresses and tool wear, a 2D finite element model was created. Furthermore, the results of the research demonstrated that machining forces and tool wear increased with increasing feed rate, whereas environmental effects were minimal. For better tool wear and residual stress, low feed rate and high-speed cutting in flood-coolant mode were suggested. Using fewer resources, Haldar et al. [17] examined machining conditions for ecological and techno-economical gains in the machining sector. The study compared traditional chips using a 25 kW precision CNC lathe equipped with micro-jets. In 15-5 PH SS turning tests, Khanna & Shah [18] looked at dry, flood, MQL, and cryogenic machining with LCO2 for tool wear. Subsurface microhardness, power consumption, and tool wear were all reduced in sustainable cryogenic machining. When compared to alternative cutting fluid procedures, flood machining provided a superior surface finish.

Zhao et al., [19] investigated Ti-6Al-4V using uncoated and TiAlN tools in circumstances of dry, MQL, flood cooling, and cryogenic spray jet cooling. Furthermore, the study demonstrated that TiAlN tools may achieve good tool life and completed surface roughness under cryogenic spray jet cooling conditions, making them appropriate for high-speed turning of Ti-6Al-4V. In [20] Choudhary and Paul found that, when taking into account specific cutting energy, dimensional deviation, and major flank wear, uncoated carbide tools were appropriate for machining Ti-6Al-4V, and multilayered TiN/TiCN/TiN tools had a longer tool life under flood cooling circumstances. Siswanto et al., [21] examined the effects of dry and flood coolant on the cutting temperature, vibration, and chip formation of stainless steel 316L. According to the investigation, T2 outperformed T1 regarding acceleration, chip thickness, vibrations, and slot milling temperature, with T2 having the highest temperature at 146°C. The effects of flood lubrication, minimal quantity lubrication, cold-air cooling, and dry machining on turning aluminum alloy EN AW-2017 were examined by Junge et al. [22]. Additionally, the study discovered that high-pressure FL provides greater fatigue strength than dry machining by improving chip removal and surface conditions at both low and high cutting rates effects of cutting settings and surroundings on tool wear and residual stresses in orthogonal cutting of AA6061-T6 were investigated by Javidikia et al. [23]. Cutting conditions, such as dry and flood-coolant modes, were found to have very little impact on machining forces. Tool wear, residual stresses, and machining forces all increased with feed rate. High-speed cutting produced the least amount of tool wear, whereas low-speed cutting produced the most. Tool wear was lessened and residual tensions were somewhat reduced in the flood-coolant mode. Kónya et al., [24] investigated the effects of oil concentration on slot milling of GTD-111 nickel-based superalloy. Results showed that a 12% oil concentration resulted in the lowest tool load and wear, while a 15% oil concentration slightly increased these factors. Higher oil concentrations resulted in less heat generation and longer tool life by reducing friction, cutting force, and tool wear. Cutting force and tool wear were maximum at 6% oil content. Race et al. [25] used coated carbide inserts to manufacture pressure vessel carbon steel (SA516) and assessed low-impact cooling techniques such as dry milling and minimal quantity lubrication (MQL). In addition, the study demonstrated cost savings, reduced energy usage, and notable improvements in surface quality and tool wear as compared to conventional flood coolant machining. A vegetable-based GCF with emulsion stability and anti-corrosion qualities was studied by Gajrani et al. [26]. The settings of the MQCF machining process were adjusted for improved results. The results indicated that using optimum MQCF process parameters increased machining performance and decreased feed force, cutting effort, coefficient of friction, and CLA surface roughness. The performance and tribological conditions of novel coatings for cryogenic-assisted machining were investigated by Zhang et al. [27], who concentrated on the friction coefficient, tool adhesion volume, and tool temperature. Also, the study found that the adhesion and friction coefficient of Ti-6Al-4V alloy are influenced by the cooling/lubrication strategy and sliding speed. Table 1 displays the comprehensive review on flood coolant.

Table 1: Systematic review on Flood coolant

Ref No.	Author (s)	Technique	Significance	Limitation/Future scope	Result
1	Geuli et al. [14]	Tool wear analysis during Inconel 718 machining with flood coolant	Flood coolant has been found to cause a small increase in tool wear and cutting speed.	Needs exploration of more coolant types and conditions	Flood coolant increases tool wear slightly compared to dry machining
2	Patil et al. [15]	Hybrid Nano flood coolant for solid and hollow end mills	Hollow-cutting tools had better tool life, smoother surface texture, and reduced spindle loads	Focus on other material types for hybrid Nano coolant testing	Hollow end mills performed better, offering longer tool life and smoother texture
3	Javidika et al. [16]	Flood and Dry coolant modes for AA6061-T6 machining	Tool wear and residual stress were reduced by using a low feed rate and high-speed cutting under flood coolant.	Analysis with varied material properties and machining speeds	Flood coolant at high speeds improves tool wear and residual stress control.
4	Haldar et al. [17]	Flood coolant with micro-jets for turning SS 304	Low-speed machining under flood cooling improved metal cutting	The study needs wider material and tool testing for validation	Flood coolant had a negative impact on ceramic tool health; micro-jet SQL was found to be optimal
5	Khanna & Shah [18]	Dry, MQL, flood, cryogenic machining with LCO2	When compared to alternative cooling methods, flood machining provided a superior surface finish.	Explore other sustainable machining techniques for wider applications	Tool wear, power consumption, and subsurface microhardness were all better with

					cryogenic machining, but surface quality was enhanced by flood machining.
6	Zhao et al. [19]	Ti-6Al-4V turning using TiAlN tools under cryogenic, MQL, dry, and flood coolant conditions.	TiAlN tools are proper for high-speed turning with superior tool life	Broaden the range of machining conditions and cooling methods	At high speeds, cryogenic spray jet cooling provided the highest surface finish and tool life.
7	Choudhary & Paul [20]	Flood cooling with multilayered tools	Improved tool life for multilayered tools under flood coolant	Needs testing under more complex machining conditions	Multilayered tools performed better under flood cooling associated to uncoated carbide tools
8	Siswanto et al. [21]	Flood coolant for stainless steel 316L	Reduced vibration and chip thickness with slightly lower acceleration	Investigate with other stainless steel grades	Flood coolant lowered the slot milling temperature and reduced vibrations
9	Junge et al. [22]	Dry, cold-air, flood, and MQL cooling for aluminum alloy turning	Flood cooling enhanced chip removal, surface state, and fatigue strength	Further research on high-pressure flood lubrication techniques	High-pressure flood lubrication provided better fatigue strength and chip removal compared to dry machining
10	Javidikia et al.[23]	Cutting of AA6061-T6 orthogonally	Investigated how cutting conditions affected residual tensions and tool wear.	Further research on different materials and speeds.	Lower residual stresses and less tool wear in flood-coolant mode.
11	Kónya et al. [24]	GTD-111 nickel-based super alloy slot milling	Examined how oil content affected tool load and wear.	Future studies on varying concentrations and different materials.	Higher oil concentrations improved tool life and reduced tool wear; flood-coolant not specifically tested.
12	Race et al.[25]	Dry milling and minimum quantity lubrication (MQL)	Evaluated low-impact cooling strategies for improved surface integrity and cost savings.	Comparison with other advanced cooling strategies	Significant improvements in tool wear and lower energy footprints compared to traditional flood coolant machining.
13	Gajrani et al. [26]	MQCF machining process optimization	Optimized vegetable-based GCF for improved machining performance and anti-corrosion properties.	Further optimization of parameters needed.	Flood-coolant was not the focus, but MQCF showed improved performance metrics

14	Zhang et al. [27]	Cryogenic-assisted machining	Investigated the performance of new coatings under different tribological conditions.	Exploration of other alloys and cooling methods.	Flood coolant effects were not specifically discussed; focused on cryogenic and lubrication strategies.

Summary of Flood Coolant in Lathe Turning Operation

Flood coolant has proven to be an effective cooling strategy, offering several advantages, especially in turning processes. It significantly helps in controlling the temperature at the cutting region, which is vital for extending tool life and maintaining cutting efficiency. In lathe machining, flood coolant improves the surface finish and aids in chip evacuation, ensuring smoother operations and reduced tool wear over time. It is particularly beneficial at lower cutting speeds and depths of cut, where it helps in minimizing burr formation and reducing vibrations, which are common issues in lathe turning. However, its effects on tool wear are not always favorable; some research suggests that, when machining at higher feed rates or depths, it may result in somewhat increased tool wear, particularly on the rake and back faces of the tool. This suggests that while flood coolant is generally beneficial for reducing cutting forces and enhancing surface quality, careful consideration of machining parameters is needed to prevent accelerated tool degradation. Overall, flood coolant remains a commonly used method in lathe operations, but it is significant to enhance its use created on the material, cutting tool, and specific conditions of the turning process to maximize its effectiveness.

Survey on Minimum Quantity Lubrication (MQL) in Lathe Turning Operations

MQL is a method used in lathe turning to reduce friction, improve tool life, enhance surface finish, lower cutting temperatures, and be eco-friendly. Rajaguru & Arunachalam, [28] examined the stress corrosion cracking resistance (SCC) and machinability of SDSS under various coolant conditions. According to the study, MQL provides better component service life and machining performance. Nadolny & Kieraś, [29] examined the supporting cooling function during internal cylindrical grinding with a compressed cooled air (CCL) stream and the MQL approach. A hybrid cooling and lubrication approach is suggested, combining cold air gun cooling with centrifugal lubrication with CCA. Okafor & Nwoguh [30] used AlTiN/TiN-coated carbide inserts to face mill Inconel 718 and compared the flow rates of MQL based on high oleic soybean oil (HOSO) with an emulsion flood coolant based on mineral oil. The study's conclusions demonstrated that the MQL flow rate of 70 ml/h offers the lowest cutting force and the longest tool life. While increasing the HOSO flow rate decreases tool wear and improves surface roughness, it also increases chip affinity and big built-up edges. For face milling Inconel 718, the study suggested using HOSO-based MQL flow rate and air pressure. Nathan et al., [31] conducted an experimental study to examine the impact of surface roughness on the MQL technique when end milling aluminum alloy 6061 grade. The study's chosen input parameters include the cutting speed, depth of cut, feed rate, and MQL flow rate. The Orthogonal Array served as the basis for this experiment (L27). The effectiveness of surface roughness was compared between components that were end-milled using the MQL technique and those that were end-milled using flooded lubrication. The results of this investigation demonstrated that the MQL approach significantly alters surface roughness levels. Race et al., [32] tested low-impact cooling techniques such as minimum quantity lubrication (MQL) and dry milling in the production of carbon steel (SA516) pressure vessels with coated carbide inserts. When compared to conventional flood coolant, the study revealed notable improvements in surface integrity and tool wear as well as reduced energy usage, suggesting financial and environmental benefits. Javid et al., [33] examined the effects of MQL and SiO2-H2O Nanofluids (NF-MQL) on tool life, wear mechanisms, surface roughness, morphology, and material removal rate in the turning of 30CrMnSiA. According to the study, DOC has a significant impact on MRR and Fr is essential for surface roughness. Surface roughness and MRR are improved by 28.34% and 5.09%, respectively, under the NF-MQL machining condition. The effects of magnetorheologically based minimum quantity lubrication of graphene oxide (GO)-based jojoba oil as a bio-lubricant on tool wear and machining performance in turning Monel K500 alloy were examined by Kulandaivel & Kumar [34]. A range of circumstances, including dry, flooded, minimum quantity lubrication, and magnetorheological settings, were used for the experiments. The effect of high-speed machining on the surface quality and chip formation of Al7075-T6 aluminum alloy was investigated by Cagan et al. [35]. When compared to dry circumstances, the study revealed better surface quality in MQL conditions. At varying cutting speeds, however, no discernible variation in chip shape or surface quality was found. In their investigation into the efficiency of MQL and solid lubricants in machining, Makhesana et al. [36] discovered that employing 20% CaF_2 powder and smaller particle sizes improved process performance, encouraging the usage of MQL and solid lubricants to promote cleaner, more sustainable manufacturing.

Khanafer et al., [37] examined the structural parameters of a vortex generator to optimize energy separation efficiency. The study showed that increasing inlet pressure and nozzle number enhances cooling, heating, and energy capacity. Energy efficiency is highest at 2° cold cone angle. The reduction of thermal conductivity improves energy separation performance. The best energy separation performance was attained by the resin vortex generator with six nozzles and a 2° cold cone angle. To minimize heat generation during orthogonal machining of EN-31 steel, Singh et al. [38] looked into the use of MQL. The results demonstrated that, in comparison to dry turning, MQL greatly decreased heat generation by 10–30%. A 55mm gap nozzle distance produced the highest cutting temperature. The cutting processes, performance enhancement behavior, film formation, and lubrication behaviors of CGNs in MQL turning, milling, and grinding were disclosed by Subramanian et al. [39]. In addition to suggesting future development options for enhanced thermal stability, CGN activity, and processing technology solutions, it concluded the influence law of molecular structure and micromorphology. To increase machining performance, Kumar et al. [40] looked at gaining MQL system potential by using a suitable combination of compressed air and cutting fluid and lowering coolant usage. Additionally, the study minimized built-up edge, decreased cutting forces, tool wear, temperature, and friction, and produced notable improvements in metal removal rate and surface smoothness. By converting client requirements into engineering specifications, Ramanathan et al. [41] developed an environmentally friendly cooling system for a lathe machine. The decision matrix method was used to choose one of the three developed concepts. Six distinct workpiece samples were used for testing, and the technique produced reduced tool wear and surface roughness. MQL and flood cooling lubrication were compared by Amli et al. [42] in a lathe turning operation on a mild steel rod. According to the study, MQL produced more segmented chips, however cutting speed and feed rate had a significant impact on surface roughness. Using Multi-position, Electrostatic, and Nano-based MQL methods, Mishra et al. [43] created a real-time framework for choosing cutting and machining fluid parameters for environmentally friendly, economical production of high-quality parts. The systematic review on MQL is shown in Table 2.

Table 2: Systematic review on MQL

Ref No.	Author (s)	Technique	Significance	Limitation/Future scope	Result
1	Rajaguru & Arunachalam [28]	MQL in machining SDSS	Superior machining performance and enhanced service life with low surface cracks and corrosion	Needs broader material testing for SCC resistance	MQL improved machinability and reduced localized corrosion and crack density
2	Nadolny & Kieraś [29]	MQL with compressed cooled air (CCL) in internal cylindrical grinding	The hybrid cooling method improved the internal grinding process efficiency	Potential for broader application in other grinding processes	MQL with CCL improved the grinding of 100Cr6 steel
3	Okafor & Nwoguh [30]	MQL using HOSO-based oil vs flood coolant in face milling Inconel 718	70 ml/h MQL flow rate provided the longest tool life and lowest cutting force	Further analysis of other MQL oils and flow rates	HOSO-based MQL showed better performance compared to flood coolant
4	Nathan et al. [31]	MQL in end milling of aluminum alloy 6061	MQL significantly reduced surface roughness compared to flooded lubrication	Needs comparison with other aluminum alloys	MQL improved surface roughness in end-milling operations

5	Race et al. [32]	MQL with vegetable-based oils in milling SA516 steel	Reduced running costs by 50%, providing environmental and economic benefits	Broaden application in other heavy manufacturing processes	MQL showed economic and environmental advantages in milling operations
6	Javid et al. [33]	NF-MQL using SiO_2-H_2O Nanofluids for turning 30CrMnSiA	Improved surface roughness and material removal rate (MRR) by 28.34% and 5.09%	Scope for further enhancement of NF-MQL technology	Nanofluids in MQL improved tool life, wear mechanisms, and MRR
7	Kulandaivel & Kumar [34]	Magnetorheological-based MQL with graphene oxide (GO) bio-lubricant	Enhanced tool wear reduction in Monel K500 turning	Need for testing under more varied machining conditions	GO-based bio-lubricants improved machining performance
8	Cagan et al. [35]	MQL in high-speed machining of Al7075-T6	MQL improved surface quality and chip formation	Requires testing under higher cutting speeds and materials	MQL provided better surface quality compared to dry machining
9	Makhesana et al. [36]	MQL with solid lubricants and CaF_2 powder	Smaller particle sizes and 20% CaF_2 powder enhanced process performance	Need to explore additional solid lubricant materials	MQL with solid lubricants enhanced process performance and sustainability
10	Khanafer et al. [37]	MQL nanofluid with Al_2O_3 nanoparticles	Reduced cutting tool temperature significantly	Needs testing with various nanoparticle concentrations	Al_2O_3 nanoparticles reduced tool temperature from 443 K to 420 K
11	Singh et al. [38]	MQL in orthogonal machining	MQL significantly reduced heat generation and cut temperature	Requires further optimization of MQL systems for other processes	MQL effectively reduced heat generation with a maximum cutting temperature at a 55 mm gap
12	Subramanian et al. [39]	MQL with compressed air and lubricant mist at the tool-workpiece edge	Siphon height, optimized air pressure, and coolant ratio for improved surface finish	Needs application on varied materials and complex machining	By optimizing system parameters, MQL decreased tool wear and enhanced surface finish.
13	Kumar et al. [40]	MQL system utilizing cutting fluid and compressed air	Investigated MQL's potential to enhance machining performance while reducing coolant usage.	Need for further optimization of fluid mixtures.	Reduced tool wear, temperature, cutting forces, and friction; enhanced metal elimination rate and exterior finish; eliminated built-up edge.
14	Ramanathan et al. [41]	Eco-friendly cooling system for lathe machine	Developed a cooling system translating customer needs	More comprehensive testing on various materials is needed.	The evaluated samples have reduced tool wear and surface roughness.

			into engineering specifications		
15	Amli et al. [42]	Comparison of MQL and flood cooling in lathe turning operation	Showed the impact of cutting speed and feed rate on surface roughness in machining.	Further studies on different materials and conditions.	MQL produced more segmented chips compared to flood cooling, indicating different chip formation.
16	Mishra et al. [43]	Real-time framework for selecting cutting and machining fluid factors	Developed eco-friendly, cost-effective manufacturing techniques using MQL approaches.	Exploration of more diverse eco-friendly fluids.	Framework enhances the selection of MQL factors for better part quality and cost efficiency.

Summary of MQL in Lathe Turning Operation

MQL has shown great promise as an alternate cooling and lubrication approach in lathe operations. It has major advantages over typical flood cooling, such as decreased coolant usage, less environmental effects, and financial savings. MQL extends tool life, minimizes surface roughness, and lowers cutting temperatures by delivering tiny quantities of lubricant precisely to the cutting zone. Furthermore, MQL improves material removal rates (MRR) while reducing heat generation, and preserving tool integrity, particularly at higher cutting speeds and with materials like aluminum alloys. The effective application depends on optimizing the cutting fluid and air mixture and using suitable tool geometries. However, MQL does have certain limits. Its performance can be impacted by feed rate, cutting speed, and lubrication type. For example, in heavy-duty activities with high heat generation, MQL may not offer adequate cooling compared to standard flood coolant systems. Furthermore, it requires optimized conditions—such as particular air pressure and flow rates—to obtain optimal advantages, and may underperform if these parameters are not properly regulated. Despite these challenges, MQL promotes the use of bio-lubricants and nanofluids to extend tool life and improve surface finishes. While it may not be appropriate for all machining conditions, MQL supports cleaner, more sustainable operations, making it an excellent choice for some lathe cooling applications.

Survey on Vortex Cooling in Lathe Turning Operations

In lathe turning, vortex cooling reduces cutting temperatures, prolongs tool life, and improves surface smoothness without the use of liquid coolants by creating cold air through a vortex tube. Fan et al., [44] investigated the flow properties in a semi-cylindrical confinement with two jet inlets using particle image velocimetry (PIV). Strongly rotating but weakly helical vortex flow was indicated by the longitudinal section's low average velocity. Convergent vortex tubes accelerate flow while preventing vortex breakdown, according to Seibold & Weigand [45]. The axial velocity is associated with subcritical and supercritical flow regimes, suggesting that flow fields are less affected by outlet conditions. To improve the efficiency of energy separation, Liang et al. [46] investigated the structural features of a vortex generator. Additionally, the study showed that the location of the temperature stagnation point is influenced by the number of nozzles as well as the inlet pressure. Energy separation in vortex tubes with varying tube diameters and lengths was examined by Ahire Yogesh et al., [47]. They found that the length and diameter of tubes with two inlet nozzles have a major effect on energy separation and cooling efficiency. To optimize geometrical parameters and compare them with earlier models, an internal facility has been established. Using the Karman vortex street phenomenon, Song et al. [48] presented a novel technique for maximizing air-cooled fuel cell cooling. It improves cooling and temperature distribution uniformity by introducing a cylindrical spoiler column before each cathode channel inlet. The impact of spoiler columns and their characteristics on cooling was confirmed using a single-channel model. According to simulation data, the spoiler column enhances the intensity of turbulent airflow, which lowers heat removal and improves energy conversion efficiency. The online vortex cooling technique, which was suggested by Wang et al. [49] and was powered by inexpensive compressed air, greatly decreased flaws in aluminum alloy wire arc additive manufacturing. The procedure minimized hydrogen absorption, enhanced formed precision, polished grains, and drastically decreased interlayer temperature. Magnesium element segregation and β phase content were improved by the fast cooling rate. Zangana et al. [50] used a CFD analysis to determine the minimum temperature of cold reversed flow and discovered that it is not in the vortex tube's cold exit. To determine the greatest cooling sites, the study contrasted convergent and divergent vortex tubes and produced greater temperature separation. To find energy-saving techniques for the tubes, Tempiam et al. [51] constructed three nozzle diameters and carried out experiments. Increasing the pressure on the vortex tube increased the energy efficiency. The best design reduced the temperature of the compressor's incoming air by 8.3°C. Indicating that increasing pressure to the vortex tube improves energy efficiency, the maximum energy-saving settings were 2.3% with 6.0 bar for the vortex tube and 0.0 bar for the low-pressure air tank. Using a laser to thermally soften the workpiece, Kuila & Melkote [52] investigated the laser-assisted micro-milling method for materials that are challenging to cut. Nevertheless, this procedure may result in the workpiece adhering to the tool, creating a built-up edge. Vortex tube cooling and minimum quantity lubrication were the two cooling and lubrication techniques examined in this paper. The combined use of both techniques reduced tool wear enhanced the dimensional correctness of the groove, and removed built-up edges, according to the results. A vortex tube for low-pressure carbon dioxide condensation was used in Zhao et al.'s self-condensation compressed carbon dioxide energy storage device [53]. Round-trip electricity, energy density, and energy efficiency of the system were 5.43 kWh/m3, 53.45%, and 61.83%, respectively. Energy density and roundtrip efficiency are both positively impacted by the storage tank's increased pressure. By creating hot and cold air flows in the Vortex Tube (VT), Thakare & Parekh [40] shortened the production cycle time. The study demonstrated that increasing entrance pressure enhances VT performance, with PA6 material exhibiting superior performance. The effects of vortex finder shape on heat transmission, temperature distribution, and cyclone separator performance were investigated by Yohana et al. [54]. Additional cooling, according to simulations, boosts collection efficiency and decreases pressure loss, although dry particles are still collected. The electrical potential of a vehicle's Solar Thermoelectric Generator (STEG) was assessed by Talawo et al., [55]. The STEG creates hot and cold air by using a turbocharger to provide air to the vortex tube. Fan et al. [56] established designs such as impingement, vortex, and double vortex cooling after comparing various cooling techniques for the leading edge of gas turbine blades. The results indicate that vortex cooling has a higher heat transfer intensity increased flow mass and anti-crossflow capabilities. In varied cross-section vortex chambers with varying draft angles, Wang et al. [57] examined the dynamics of heat transmission and flow. The results demonstrated that vortex chambers with greater draft angles perform better in terms of heat transfer and flow. Aerodynamic loss reduced with temperature ratio, pressure drop increased with draft angle, and heat transfer intensity increased with draft angle. Lower aerodynamic loss and more intense heat transfer were observed in the vortex chamber with $\beta > 0°$. With an emphasis on CO_2 utilization, Kaya et al. [59] examined the performance of two counter-flow Ranquee-Hilsch Vortex Tubes (RHVT) with the same geometrical characteristics. The effect of vortex cooling on cutting performance and machining techniques was investigated by Gürkan et al. [60]. According to the study, vortex cooling has a more favorable effect on turning and milling operations than conventional liquid cooling, dry machining, and traditional air cooling techniques, but not as much as cryogenic and MQL cooling techniques. Heat transport properties in a vortex tube were investigated by Modi et al. [61], taking into account variables such as cross-section, nozzle area, and L/D ratio. The study investigated the possibility of improving cooling performance using a cooling system. The net energy transfer rate from the chilly core region to the heated outer region was found to rise with the use of a cooling system. Using cooled CO_2 gas, Mahapatro et al. [62] turned Ti-6Al-4V, producing changes in temperature, cutting force, and surface roughness. Comparing the suggested cooling system to dry cutting, the results indicated that it increased cutting force marginally while improving cutting temperature and surface roughness. By simulating a counter-flow vortex tube with the computational fluid dynamics program STAR-CCM+, Matveev & Leachman [63] investigated the usage of cyclonic-type extensions in augmenting vortex tubes. The study discovered an effective high-capacity vortex tube design with an intermediate-size extension and validated the numerical method. The performance of two counterflow Ranquee-Hilsch Vortex Tubes (RHVT) with the same geometrical characteristics was examined by Kaya et al. [64]. The study used brass and polyamide nozzles to examine the usage of CO_2 in the RHVT. The study calculated the second law efficiency for various working situations and discovered a 14-point L/D ratio. 76.9 K was the greatest total temperature differential. Using vortex tubes, Celik et al. [65] sought to increase the startability of diesel engines in cold climates. A six-cylinder, four-stroke, direct-injection diesel engine with a vortex tube to raise the temperature of the intake air was employed in the investigation. According to the findings, using vortex tubes decreased combustion instability, idling time, and cranking times. Table 3 displays the systematic review of vortex cooling.

Table 3: Systematic review of Vortex cooling

Ref No.	Author (s)	Technique	Significance	Limitation/Future scope	Result
1	Fan et al. [44]	Particle Image Velocimetry (PIV)	Utilized in semi-cylindrical confinement with two jet inlets to comprehend vortex movement.	Vortex flow that is strongly rotating but weakly helical; the effects of other geometrical adjustments could be examined.	Low average velocity in the longitudinal section, indicating controlled and stable flow.
2	Seibold & Weigand [45]	Convergent Vortex Tubes	Revealed suppression of vortex breakdown due to flow acceleration.	Future studies can explore more complex flow conditions to fully understand axial velocity effects.	High axial velocity, linked to suppressed vortex breakdown and flow stability.
3	Liang et al. [46]	Vortex Generator Optimizatio n	Investigated structural parameters to optimize energy separation efficiency.	Further optimization of nozzle number and pressure settings could enhance efficiency further.	High energy separation efficiency with optimal nozzle number and inlet pressure.
4	Ahire Yogesh et al. [47]	Double Inlet Nozzles	We have studied the impact on cooling efficiency and energy separation in vortex tubes.	The study could expand to other tube geometries to assess efficiency.	High cooling efficiency and energy separation with double inlet nozzles.
5	Song et al. [48]	Karman Vortex Street Phenomeno n	Used to optimize cooling for air-cooled fuel cells.	Application of this phenomenon to other cooling applications should be explored.	High cooling performance for air-cooled fuel cells, optimizing energy usage.
6	Wang et al. [49]	Online Vortex Cooling in Wire Arc Additive Manufacturi ng	Proposed a low-cost compressed air-powered method to reduce defects in aluminum alloys.	Additional trials could confirm its effectiveness across other materials and manufacturing processes.	Low defect rate in aluminum alloy Wire Arc Additive Manufacturing using vortex cooling.
7	Zangana et al. [50]	Vortex Tube Temperatur e Analysis	Determined the lowest temperature of cold reversed flow outside of the vortex tube's cold exit.	Further studies on controlling cold reversed flow temperature.	Low cold flow temperature, achieving desired cooling effects.
8	Tempiam et al. [51]	Nozzle Size Experiment s	Focused on improving energy efficiency by experimenting with different nozzle sizes.	Future work could look into other geometrical factors affecting energy efficiency.	High energy efficiency is achieved by increasing pressure on the vortex tube.
9	Kuila & Melkote [52]	Vortex Tube Cooling with Laser-Assisted	Explored cooling on hard-to-cut stainless steel (A286) and its effects.	Further exploration of micro-milling in combination with vortex	Low burr formation and controlled groove changes, improving machining quality.

		Micro Milling		cooling across a broader range of metals.	
10	Zhao et al. [53]	CO2 Energy Storage with Vortex Tube	Suggested use of a vortex tube for low-pressure condensation in a compressed carbon dioxide energy storage device.	Additional studies could assess long-term viability and energy storage capacity.	High efficiency in CO2 condensation with controlled vortex tube cooling.
11	Thakare & Parekh [54]	Vortex Tube Performance with PA6 Material	Demonstrated enhanced performance with increased entry pressure using PA6 material.	Investigation into other materials could be pursued to further improve performance.	High performance with PA6 material under increased entry pressure.
12	Yohana et al. [55]	Vortex Finder Geometry in Cyclone Separator	Examined its impact on separator performance, temperature distribution, and heat transfer.	Future work could explore the effect of more complex geometries and the collection of finer particles.	High collection efficiency and low-pressure drop, ensuring improved performance.
13	Talawo et al. [56]	Vortex Tube in Solar Thermoelectric Generator (STEG)	Evaluated an STEG system using a turbocharger for vortex tube air supply, producing hot and cold air.	Further optimization of turbocharger and vortex integration can enhance energy efficiency.	High efficiency in generating both hot and cold air for the STEG system.
14	Fan et al. [57]	The Gas Turbine Blade Vortex Cooling System	Compare several gas turbine blade cooling techniques, such as vortex and impingement cooling.	Future exploration into more blade designs and cooling methods.	Vortex cooling and high heat transfer intensity enhance anti-crossflow performance.
15	Wang et al. [58]	Vortex Chamber Flow Analysis	Examine the dynamics of heat transfer and flow in vortex chambers with varying draft angles.	The impact of different chamber geometry on performance may be investigated in future research.	Superior performance with optimized flow behavior and variable cross-section vortex chambers.
16	Kaya et al. [59]	Ranquee-Hilsch Vortex Tubes (RHVT) for CO2	Analyzed two RHVTs with identical properties, focusing on CO2 usage.	Future studies could explore additional gases or hybrid systems for cooling applications.	High cooling efficiency in CO2-based systems using RHVT
17	Gürkan et al.[60]	Vortex cooling in machining	Examined the impact of vortex cooling on turning and milling performance compared to other methods.	Further investigation into cost-effectiveness and optimization is needed.	Vortex cooling showed improved cutting performance over dry, conventional liquid, and air cooling, but was less effective than

					cryogenic and MQL cooling methods.
18	Modi et al. [61]	Heat transfer in vortex tubes	Investigated how cross-section, nozzle area, and L/D ratio affect cooling efficiency in vortex tubes.	Need for optimization of cooling system parameters.	Increased energy transfer from cold inner to hot outer regions with the use of a cooling system.
19	Mahapatro et al. [62]	Ti-6Al-4V is being turned by cooled CO_2 gas.	Enhanced cutting temperature control and surface finish in turning operations.	Compared to dry cutting, there is a minor increase in cutting force.	Reduced increase in cutting force and an improvement in surface roughness and cutting temperature.
20	Matveev & Leachman [63]	Cyclonic-type extensions in vortex tubes	Validated CFD simulation to design efficient, high-capacity vortex tubes.	Further validation is needed in practical settings.	Identified efficient vortex tube design with intermediate-size extension for enhanced performance.
21	Kaya et al. [64]	CO_2 in counterflow RHVT with polyamide and brass nozzles	Analyzed RHVT performance using different nozzle materials and L/D ratios for efficient cooling.	A broader analysis of various working conditions is suggested.	Achieved maximum temperature difference of 76.9 K with a 14-point L/D ratio.
22	Celik et al. [65]	Vortex tubes in diesel engine startability	Improved diesel engine performance in low temperatures by warming intake air	Exploration of long-term effects on engine components.	Reduced cranking periods and idling time improved engine stability in cold conditions.

Summary of Vortex Cooling in Lathe Turning Operation

Vortex cooling has emerged as an ensuring cooling method, with benefits such as better cooling efficiency, energy separation, and improved machining quality. The process successfully lowers the temperature of the workpiece and cutting tools, especially in high-precision operations such as turning and milling. It has been demonstrated to provide excellent cooling performance by optimizing flow behavior, reducing vortex collapse, and increasing heat transfer intensity, making it ideal for complicated machining operations. Furthermore, vortex cooling has proven considerable reductions in burr development, better surface finishes, and decreased defect rates during machining. This cooling technology is also energy-efficient, as good performance may be attained by modifying factors such as entrance pressure and nozzle design. Despite these benefits, there are certain limits, such as the necessity for further optimization of vortex tube settings and experimentation with other materials and geometries. Future research can focus on improving these elements to maximize cooling advantages for a broader variety of materials and processes. Overall, vortex cooling is a low-cost, efficient cooling option for lathe operations, notably for extending tool life and improving machining performance under difficult conditions.

HEAT TRANSFER ANALYSIS USING ANSYS

Heat transfer analysis using ANSYS involves simulating the transfer of heat in different systems to study conduction, convection, and radiation processes. ANSYS enables engineers to model complex geometries, apply material properties, and set boundary conditions to predict temperature distribution and thermal behavior. The software uses finite element methods to solve heat equations, providing insights into thermal stresses and energy efficiency. This analysis is crucial for optimizing designs in industries like automotive, aerospace, and manufacturing. It helps improve product reliability, safety, and performance under various thermal conditions.

Demirağ et al., [66] evaluated the thermal performance of a novel type conic vortex generator (NTCVG) in a rectangular duct with an aspect ratio of AR=10. The study analyzed various attack angles, blade angles, and scale ratios in the range of Re=5000-25000. Moreover, the study used numerical analysis to understand the relationship between flow structure and convective heat transfer mechanism, revealing Reynolds-averaged fluid velocity, vorticity distributions, temperature, and Nusselt number distributions. Shlash et al., [67] investigated the flow and heat transfer of turbulent fluid flow through channels using various vortex generator designs. The finite volume method (FVM) and SIMPLE algorithm approach solved continuity, momentum, and energy equations. Geometric factors like step height and Reynolds number are analyzed, with the quarter circle vortex generator showing the best thermal-hydraulic performance. Li et al., [68] designed three twist ratios (TR) for an experimental SCO_2 water-cooled counterflow tube-in-tube heat exchanger. The convective heat transfer was simulated using ANSYS CFX, and the optimal TRs were found using the performance evaluation criterion curve and friction factor ratio ≤5. The best heat transfer enhancement was found at a point with 2-3 times better heat transfer than in water or airflow. The optimal TR depends on SCO_2 operational conditions, with TR = 3.78 being the optimal TR for most cases. Brodnianska et al., [69] analyzed heat transfer coefficients, Nusselt numbers, thermal performance, Colburn factor, and friction factor for wavy and cylindrical vortex channels. Results showed that wavy channels with cylindrical vortex generators enhance the Colburn factor by 2.48 and 3.28 times compared to smooth channels. The study also presented new correlating equations for channel height and volumetric flow rate. Inserting cylindrical vortex generators significantly improved heat transfer efficiency and reduced energy consumption.

Sharma et al., [70] evaluated the impact of non-dimensional base width, height, and flow attack angle on the heat transfer of a tube wall graphene (TWVG) for different flow angles. Results showed that TWVG improved heat transfer through flow impingement and vortex formation. Heat transfer decreased with increasing flow attack angle, but the friction factor increased. Greater height and base width enhanced heat transfer and friction factor, with maximum enhancements in Nusselt number and friction factor. Feng et al., [71] investigated heat transfer and fluid flow in circular tubes with multi-delta winglets vortex generators. Results showed that vortex pairs near the boundary layer enhance fluid flows, while higher blockage ratios and winglet pair numbers negatively affect flow. The study also provided insights for designing winglet structures and optimizing flow fields through similarity analysis. Saini et al., [72] analyzed the thermal-hydraulic performance of fin and tube heat exchangers with curved delta winglet vortex generators (CDWVG) with or without circular holes. Results showed that using CDWVGs with circular punched holes significantly improves FTHE efficiency, with the 6-hole configuration being the most effective. This results in reduced friction and improved performance. Lertnuwat, [73] investigated airflows with Reynolds number, varying hole-arrangement patterns. Results showed that hole number significantly affects Nusselt number, with single-hole vortex generators having the highest averaged Nusselt number. Large, well-organized vortices were more efficient for heat transfer. Table 4 displays the Systematic review of Heat transfer analysis using ANSYS.

Table 4: Systematic review of Heat transfer analysis using ANSYS

Ref No.	Author (s)	Technique	Significance	Limitation/Future scope	Nusselt number (Nu)	Result
1	Demirağ et al. [66]	Novel Type Conic Vortex Generator (NTCVG) in a rectangular duct	Evaluated attack angles, blade angles, and scale ratios over Re=5000–25000; analyzed flow structure and convective heat transfer mechanism.	Further optimization of attack angles and scaling for practical applications.	8.24	Revealed Reynolds-averaged velocity, vorticity, and Nusselt number distributions.
2	Shlash et al. [67]	Turbulent fluid flows through channels using	Used FVM and SIMPLE algorithm to solve equations; analyzed geometric	Needs experimental validation for	0.06-0.16	The quarter-circle vortex generator showed the best

		various vortex generator designs.	factors like step height and Reynolds number.	diverse flow conditions.		thermal-hydraulic performance.
3	Li et al. [68]	SCO2 water-cooled counterflow tube-in-tube heat exchanger	Designed three twist ratios (TR) and used ANSYS CFX simulation to optimize heat transfer.	Applicability depends on specific operational conditions of SCO2.	3.63-7.29	Achieved 2–3 times better heat transfer than water or airflow; optimal TR = 3.78 for most cases.
4	Brodnianska et al. [69]	Wavy and cylindrical vortex channels	Analyzed Colburn factor, friction factor, heat transfer coefficients, and Nusselt numbers.	More extensive datasets are required for developing universal correlations.	2.6- 3.2	Enhanced Colburn factor by 2.48–3.28 times compared to smooth channels.
5	Sharma et al. [70]	Tube Wall Graphene Vortex Generator (TWVG)	Improved heat transfer through flow impingement and vortex formation.	The friction factor increases with higher flow attack angles; material cost analysis.	2.61-2.96	Maximum enhancements in Nusselt number and friction factor.
6	Feng et al. [71]	Multi-delta winglet vortex generators in circular tubes	Investigated vortex pairs near the boundary layer for enhanced fluid flows.	Higher blockage ratios and winglet pair numbers negatively affect flow; and require design optimization.	106.2-108.0	Insights for designing winglet structures and optimizing flow fields via similarity analysis
7	Saini et al. [72]	Curved Delta Winglet Vortex Generators (CDWVG) with circular holes	Improved FTHE efficiency with circular punched holes; analyzed thermal-hydraulic performance.	Scope for investigating alternative hole configurations and materials.	77.25-42.51	6-hole configuration significantly improved efficiency by reducing friction.
8	Lertnuwat [73]	Airflows with varying hole-arrangement patterns	Showed that single-hole vortex generators produced the highest averaged Nusselt number.	Needs study on complex hole patterns and their long-term effects on flow dynamics.	0.82-1.38	Large, well-organized vortices were the most efficient for heat transfer.

COMPREHENSIVE ANALYSIS AND DISCUSSION

Heat control in lathe turning processes is crucial for extending tool life, assuring dimensional accuracy, and producing high-quality surface finishes on workpieces. To solve this difficulty, a variety of cooling strategies are used, each with its own set of benefits and limits. Flood coolant is frequently utilized because of its capacity to remove enormous amounts of heat, especially in high-speed cutting applications. It offers effective cooling and lubrication, hence reducing tool wear and improving surface finishes. However, the vast amounts of coolant required can be expensive and environmentally harmful owing to disposal issues.

MQL consumes substantially less coolant by supplying tiny quantities directly to the cutting zone. This makes MQL an ecologically benign solution while yet providing enough cooling and lubrication in many applications, particularly those involving modest speeds. MQL also decreases the mess caused by flood coolant and can extend tool life in some materials. However, it may be less successful at regulating heat in high-speed or heavy-duty processes, restricting its use in some industrial environments.

Vortex cooling, a more sophisticated and dry cooling method, uses compressed air to generate a cold air stream directed at the cutting tool. This approach is especially useful for high-speed machining where heat management is critical, providing greater temperature regulation without the need for liquid coolants. Vortex cooling is especially useful in situations that need precise control over tool temperature, such as cutting heat-sensitive materials or preventing coolant contamination. However, the setup for vortex cooling can be more complicated, and its efficacy is dependent on a steady supply of compressed air. Regardless of these factors, vortex cooling stands out for its capacity to function in clean, dry conditions, making it a suitable choice for specific high-precision jobs in lathe-turning processes.

CHALLENGES AND FUTURE TRENDS

Challenges

- Flood coolant and MQL are two examples of conventional cooling systems whose ecological effects are still difficult to address. Eco-friendly fluids with little environmental impact must be used, however, this needs a lot of testing. Adoption is complicated by the need to balance cost, performance, and environmental benefits. Traditional coolant usage is made more difficult by regulations and disposal standards. Combining biodegradable materials with renewable resources is necessary for this.
- One of the biggest challenges is to formulate cutting fluids optimally for certain machining processes and materials. This entails modifying variables including lubricity, thermal conductivity, and viscosity. It frequently takes trial-and-error testing to get the ideal balance. More attention must be paid to the cost-effectiveness and scalability of optimized fluids for industrial applications. There is additional work to be done to develop universal fluids for a variety of tasks.
- Complementary cooling solutions are necessary for advanced manufacturing techniques like additive manufacturing. The localized heat and defect issues of these processes are frequently ignored by conventional systems. Redesigning machine tools is necessary to integrate cryogenic or vortex cooling systems. This adaptation is made more difficult by the absence of standards and rules. Another challenge is ensuring compatibility across different materials.
- One constant problem is accurately predicting tool wear under various cooling and machining settings. IoT and sophisticated sensor systems must be integrated for real-time monitoring. Widespread adoption in small and medium-sized businesses is hampered by high upfront expenditures and ongoing upkeep. Complexities in data collecting and interpretation frequently result in less-than-ideal choices. This highlights the need for reliable AI-powered predictive maintenance solutions.
- Implementing high-performance coolants, such as MQL with nanofluids and cryogenic systems, is frequently expensive. Small businesses find it difficult to justify these expenditures, and it's challenging to strike a balance between upfront expenses and long-term operational savings. The problem is made worse by a lack of resources for operators' advanced cooling system training. Economic feasibility studies and policy incentives are necessary for widespread adoption.

Future Trends

- Coolant flow control and fluid optimization using AI-driven solutions are new developments. Coolant flow rates can be dynamically modified by algorithms in response to current machining conditions. Ideal cooling parameters and tool wear prediction are aided by machine learning algorithms. This automation improves machining efficiency and decreases resource waste. AI is also capable of forecasting coolant system repair schedules.
- Research on fluids made from natural oils and renewable resources is progressing. These fluids are designed to provide excellent performance with the least amount of environmental impact. For safer industrial uses, non-toxic and biodegradable additives are being created. Completely carbon-neutral fluids are among the upcoming developments. These patterns support the objectives of environmental sustainability worldwide.
- Using methods like MQL, vortex cooling, and cryogenic chilling together shows a lot of promise. Complex machining tasks might benefit from the cooling performance optimization offered by these hybrid systems. While addressing the drawbacks of stand-alone approaches, studies concentrate on utilizing individual capabilities.

Implementation is a major area of focus for multi-material machining applications. Advanced hybrid systems could provide unparalleled energy economy and precision.

- Al2O3, SiO2, and graphene oxide nanoparticle-containing nanofluids are becoming more and more well-liked. These provide improved heat dissipation, decreased friction, and enhanced thermal conductivity. Stable nanoparticle dispersions and economical manufacture are examples of upcoming advancements. Particularly intriguing applications include additive manufacturing and high-speed machining. The goal of the study is to improve compatibility under various machining circumstances.
- Coolant efficiency and tool condition monitoring systems powered by the Internet of Things are becoming more popular. Real-time temperature and wear data are provided by sensors built into cutting tools. Alerts for predictive maintenance and remote monitoring are made possible by cloud-based technologies. This tendency is especially pertinent to smart production setups that comply with Industry 4.0. Future developments concentrate on scalable, reasonably priced IoT solutions for small businesses.

CONCLUSION

The research undertaken in this study meticulously investigates the comparative effectiveness of three distinct cooling methodologies utilized in lathe turning operations, which include flood coolant, MQL, and vortex cooling. It is observed that flood coolant proves to be particularly effective in heavy-duty operational contexts, however, it concurrently presents significant environmental and economic challenges stemming from the necessity for substantial volumes of coolant, which can lead to increased waste and disposal issues. In contrast, MQL emerges as a more sustainable alternative that effectively provides sufficient lubrication in moderate-speed operational scenarios, thus aligning with contemporary environmental standards and reducing overall coolant consumption. Vortex cooling is an advanced technology designed to improve performance in high-speed precision tasks, leading to improved machining outcomes. The study emphasizes the importance of selecting the right cooling technique, and considering factors like operation, material characteristics, and desired performance outcomes. Optimizing cooling strategies is not just a matter of preference but a fundamental aspect that can enhance tool life, surface quality, and operational efficiency in machining processes. This study suggests that understanding and implementing suitable cooling methods can help balance operational performance and sustainability in manufacturing environments. It provides valuable insights for future research and practical applications in machining and manufacturing technology. Selecting the right cooling strategy can lead to advancements in productivity and environmental stewardship in machining practices.

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