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# Development of Smart Cooling Optimization System for CNC Machining Applications

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**Abstract**

*In modern manufacturing industries, achieving high machining accuracy, improved surface finish, and extended tool life remains a significant challenge, particularly during the machining of hard materials where excessive heat generation at the tool–workpiece interface is inevitable. Conventional coolant systems often suffer from limitations such as manual control, inconsistent flow rates, and inefficient coolant usage, which negatively impact productivity and environmental sustainability. This paper presents the design and development of an automated coolant control system for CNC machining applications using an embedded microcontroller platform. The proposed system integrates a non-contact temperature sensor (MLX90614) and a flow control mechanism to monitor real-time thermal conditions and regulate coolant supply accordingly. The system operates on a multi-level cooling strategy, activating the coolant pump only when the temperature exceeds predefined thresholds and deactivating it when optimal conditions are restored. The implementation utilizes an Arduino-based control unit, relay module, and DC pump to achieve precise coolant delivery. This intelligent approach minimizes coolant wastage, reduces energy consumption, and enhances machining efficiency. Experimental results indicate improved thermal management, better surface quality, and increased tool life compared to conventional cooling methods. The developed system provides an economical, easy-to-operate, and adaptable approach that can be employed with different machining equipment, supporting intelligent production methods along with environmentally responsible manufacturing operations.*

**Keywords:** CNC machining, automatic coolant system, embedded system, arduino UNO, temperature sensor (MLX90614), smart cooling, tool life enhancement, surface roughness, flow control system, industrial automation, thermal management, multi-level cooling, sustainable manufacturing, internet of things (IoT).

## INTRODUCTION

The continuous development of modern manufacturing methods has greatly enhanced the need for improved accuracy, higher production rates, and better operational performance in machining applications. Computer Numerical Control (CNC) machines have emerged as a key solution to meet these industrial requirements by automating machine tool operations using programmed instructions. CNC machining enables the production of complex geometries with high accuracy and repeatability, making it widely used in industries such as aerospace, automotive, and electronics.

However, during machining operations—especially when working with hard materials—excessive heat is generated at the tool–workpiece

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interface due to friction and cutting forces. This heat adversely affects tool life, surface finish, and dimensional accuracy. Traditional coolant systems, which are often manually controlled, may lead to inconsistent coolant flow, excessive usage, and environmental concerns. To overcome these challenges, there is a need for intelligent and automated coolant systems that can adapt to real-time machining conditions.

This paper proposes an automated coolant control system based on embedded technology, which monitors temperature variations and regulates coolant flow efficiently. The system aims to enhance machining performance, reduce coolant wastage, and support sustainable manufacturing practices.

**Overview of CNC Machines**

Computer Numerical Control (CNC) machines are sophisticated production systems that operate through programmed computer commands to manage the motion and functioning of equipment including turning machines, milling units, grinding setups, and drilling devices. These machines operate based on coded instructions (G-code and M-code), which define parameters such as tool path, speed, feed rate, and cutting depth.

A CNC system typically consists of key components including the Machine Control Unit (MCU), input devices, drive systems, feedback mechanisms, and display units. The MCU functions as the central processing unit of the system, analyzing the programmed commands and producing control actions to ensure accurate movement and operation of the machine tool. Feedback systems continuously monitor parameters such as position and velocity to ensure accurate machining.

CNC machines offer numerous advantages over conventional machines, including higher precision, reduced human intervention, consistent quality, and the ability to produce complex shapes efficiently. These features make CNC technology essential in modern manufacturing environments.

**Working Principle of CNC Machine**

The operating mechanism of a CNC machine relies on the combination of computerized programming and automatic control technology. In the beginning stage, the component design is developed through computer-aided design (CAD) and computer-aided manufacturing (CAM) applications. This program is then converted into machine-readable code and fed into the Machine Control Unit (MCU).

The MCU processes the input instructions and generates corresponding motion commands for the machine tool. These commands are transmitted to the drive system, which controls the movement of motors and actuators along different axes (X, Y, and Z). The machine equipment subsequently carries out the necessary manufacturing processes including material cutting, hole making, and component shaping operations.

A feedback system continuously monitors the position and speed of the tool using sensors and sends this data back to the MCU. The MCU compares the actual output with the desired input and makes necessary corrections in real time, ensuring high precision and accuracy. This closed-loop control mechanism enables CNC machines to maintain consistent performance and produce high-quality components (Figure 1).

## LITERATURE REVIEW

The increasing demand for precision machining and sustainable manufacturing has led to extensive research on advanced cooling techniques and automated coolant systems in CNC machining. Various studies have focused on improving tool life, surface quality, and energy efficiency through optimized coolant delivery methods.

Araveeti C. Sekhara Reddy [1] investigated recent advancements in CNC machining systems, highlighting the importance of coolant-fed tooling in reducing friction and temperature at the tool–

workpiece interface. The study concluded that pressurized coolant systems significantly improve machining performance and productivity.

Weber and Weber [2] analyzed the impact of thermo-elastic deformations on machining accuracy and emphasized the role of fluid power systems in maintaining thermal stability. Their work demonstrated that effective cooling strategies are essential for achieving high precision and energy-efficient manufacturing.

Braham-Bouchnak et al. [3] studied high-pressure coolant (HPC) assisted machining and reported notable improvements in tool life, chip formation, and surface integrity. The results showed that controlled coolant delivery reduces cutting forces and enhances overall machining efficiency.

Tai et al. [4] explored Minimum Quantity Lubrication (MQL) technology as an alternative to conventional coolant systems. Their findings indicated that MQL reduces coolant consumption, energy usage, and environmental impact while maintaining acceptable machining performance. However, challenges remain in high-temperature and heavy-duty machining applications.

The study examined machining processes with reduced or no coolant usage, emphasizing their environmental and economic advantages. It was highlighted that although dry machining can eliminate coolant-related hazards, it may adversely affect tool life and surface quality under certain operating conditions.

Modern studies have increasingly concentrated on incorporating sensor technology and automated control methods into cooling arrangements. Zhao and co-researchers investigated these developments in detail. [5] demonstrated that sensor-based cooling systems with feedback control can significantly reduce energy consumption by activating coolant flow only when required. Similarly, Patel and Sharma [6] proposed a microcontroller-based multi-level cooling approach, which improves thermal management by gradually adjusting cooling intensity based on temperature variations.

Nguyen et al. [7] emphasized the environmental benefits of automated coolant systems, showing that controlled coolant usage reduces waste and contamination without affecting machining performance. Fernandez and Lopez [8] introduced non-contact infrared temperature sensing techniques for real-time monitoring in high-speed machining environments, improving system responsiveness and reliability.

Further advancements include IoT-based monitoring and intelligent cooling strategies. Gupta and Kumar [9] developed a smart cooling system with remote monitoring capabilities, enabling predictive maintenance and improved operational efficiency. Miller [10] discussed the application of PID controllers in automated cooling systems to achieve stable temperature regulation and avoid frequent switching.

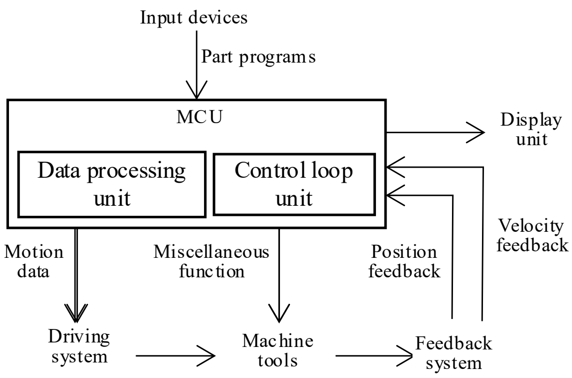



**Figure 1.** Working principle of CNC machine.

From the reviewed literature, it is evident that while significant progress has been made in coolant technologies and automation, there is still a need for cost-effective, real-time adaptive cooling systems that combine sensor-based monitoring with simple embedded control. The proposed system in this paper addresses these gaps by implementing a microcontroller-based automatic coolant system with multi-level control, ensuring efficient thermal management, reduced coolant wastage, and improved machining performance.

## COMPONENTS OF A CNC MACHINE

A Computer Numerical Control (CNC) machine is composed of several integrated components that work together to achieve precise and automated machining operations. Every element performs an essential function in maintaining precision, operational effectiveness, and dependable system performance.

### Input Devices

Input units are utilized for feeding the part program instructions into the CNC control system. These programs contain coded instructions (such as G-code and M-code) that guide machine operations. Common input methods include computer interfaces, USB devices, and direct numerical control (DNC) systems.

### Machine Control Unit (MCU)

The Machine Control Unit functions as the central processing section of a CNC machine. It interprets the input program, performs necessary calculations such as interpolation, and generates control signals. The MCU also manages auxiliary functions like coolant control, spindle speed regulation, and tool changing operations.

### Machine Tool

The machine tool represents the physical section of a CNC system responsible for carrying out machining operations. It consists of elements like the spindle unit, cutting instruments, and work holding table. The system enables motion through different axes, including X, Y, and Z, to produce accurate geometry and required dimensions.

### Driving System

The driving system converts electrical signals from the MCU into mechanical motion. It consists of servo motors or stepper motors, amplifier circuits, and ball screws. These components ensure accurate positioning and movement of the machine tool.

### Feedback System

The feedback system includes sensors and transducers that continuously monitor parameters such as position, speed, and displacement. This information is sent back to the MCU to compare with the programmed values, allowing real-time error correction and ensuring high precision through closed-loop control.

### Display Unit

The display unit serves as a communication interface through which the operator can monitor and control CNC machine operations. It displays program details, machining parameters, system status, and error messages, enabling effective monitoring and control of operations.

## TYPES OF CNC MACHINES

CNC machines are classified based on their machining operations and applications. Each type is designed to perform specific tasks with high precision and efficiency.

### CNC Milling Machines

CNC milling machines operate with rotating cutters that eliminate unwanted material from the job component. These systems are capable of carrying out tasks like surface milling, groove cutting, hole making, and profile shaping. Industries commonly employ these machines for manufacturing intricate components, dies, and experimental models (Figure 2).

**CNC Lathes**

CNC lathes are mainly designed for turning applications. During this machining method, the work material spins continuously, whereas the cutting device stays fixed in position. These machines are ideal for manufacturing cylindrical components such as shafts, bolts, and bushings (Figure 3).

**Turning Centers**

Turning centers are advanced versions of CNC lathes capable of performing multiple machining operations, including drilling, tapping, and milling, in a single setup. They improve productivity and reduce machining time (Figure 4).

**CNC Grinding Machines**

CNC grinding machines use abrasive wheels to achieve high surface finish and dimensional accuracy. These machines are commonly used in finishing operations for hardened materials (Figure 5).

**CNC Drilling Machines**

CNC drilling machines are designed to create precise holes in a work piece. They are widely used in mass production industries where accuracy and repeatability are critical (Figure 6).

**CNC Boring Machines**

CNC boring machines are designed to increase the diameter of pre-existing holes with excellent accuracy. These systems are extensively utilized in heavy industrial applications and fabrication of large-sized mechanical parts.

**Figure 2.** CNC Milling Machines.

**Figure 3.** CNC Lath.

**Figure 4.** CNC Turning.

**Figure 5.** CNC Grinding.

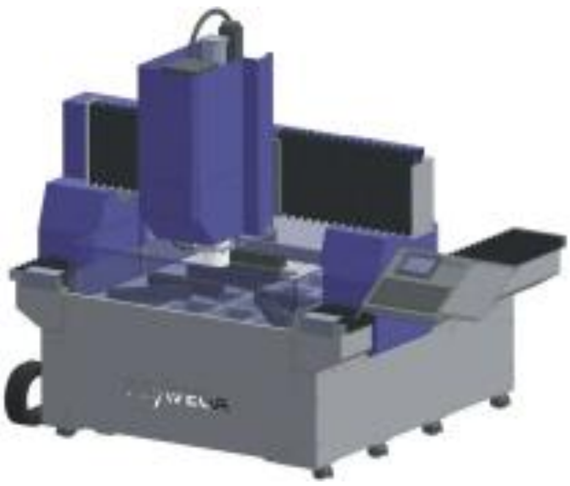


**Figure 6.** CNC Drilling.

**Electrical Discharge Machines (EDM)**

EDM equipment removes material through controlled electrical discharges between the tool and work piece. This technique is highly effective for processing tough conductive metals that cannot be machined easily by traditional cutting operations.

### Laser Cutting Machines

Laser cutting systems employ a concentrated laser source to slice materials with superior precision and very low heat deformation. Such machines are broadly applied in metal sheet processing and electronic component production industries.

## FUNCTIONS OF CNC MACHINES

The primary function of Computer Numerical Control (CNC) machines is to automate and precisely control machining operations using programmed instructions. CNC machines interpret coded instructions such as G-code and M-code, which define parameters including tool path, spindle speed, feed rate, and depth of cut. Based on these instructions, the system controls the motion of the cutting tool and workpiece along multiple axes, ensuring accurate positioning and coordinated movement. The CNC controller regulates speed and feed rate to maintain optimal cutting conditions, thereby improving surface finish and reducing tool wear. Additionally, CNC machines manage tool operations, including tool selection and automatic tool changing, enabling multiple machining processes to be carried out efficiently without manual intervention. A feedback system continuously monitors parameters such as position and speed, allowing real-time error correction and ensuring high precision. Furthermore, CNC machines automate auxiliary functions such as coolant control, lubrication, and spindle operations, enhancing overall productivity. Modern CNC systems also provide process monitoring and diagnostic features, displaying system status, errors, and alarms, which assist in maintaining consistent performance and minimizing downtime.

## ADVANTAGES AND DISADVANTAGES OF CNC MACHINES

Computer Numerical Control (CNC) machines offer numerous advantages that make them essential in modern manufacturing industries. One of the primary benefits is their high precision and accuracy, which enables the production of complex components with minimal error. CNC machines can operate continuously for long durations, improving productivity and reducing downtime. They ensure consistent quality in mass production, as the same program can be repeated without variation. Additionally, CNC machines reduce human intervention, thereby minimizing manual errors and improving safety. These systems can manufacture detailed and complicated shapes that are not easily created through traditional machining methods. Furthermore, CNC technology enhances efficiency, reduces labor requirements, and allows quick modifications in design through simple program changes.

Despite these advantages, CNC machines also have certain limitations. The initial investment cost of CNC machines is relatively high, making them less affordable for small-scale industries. Maintenance and repair costs can also be significant due to the complexity of components. CNC machines require skilled personnel for programming and operation, which may increase training costs. In addition, the replacement of parts and cutting tools can be expensive. Another drawback is the dependency on computer systems; any technical failure or software issue can lead to complete production stoppage.

## INTRODUCTION TO EMBEDDED SYSTEMS

An embedded system refers to an integrated arrangement of hardware and software created for carrying out a dedicated function within a larger electronic setup. Unlike conventional computers designed for multiple purposes, embedded systems focus on particular operations in areas such as automobiles, medical equipment, industrial automation, and household electronics. These systems are developed to deliver dependable performance, quick response, and reduced human involvement during operation. In most cases, an embedded system contains a microcontroller or microprocessor, storage memory, input and output modules, along with specialized software responsible for managing system activities (Figure 7).

### Hardware and Software

Embedded systems contain both physical hardware elements and software programs working together for effective operation. Hardware components generally include processors, memory sections, sensors, actuators, and communication modules. The processor functions as the primary controlling unit that interprets instructions and supervises different activities, whereas memory devices retain application data and program instructions. Peripheral units support communication between the system and the surrounding environment.

The software section consists of programs developed using languages such as C, Assembly Language Programming (ALP), or various advanced programming languages. This software, commonly identified as firmware, remains stored inside memory and is executed by the processor to regulate hardware functions. Proper coordination between hardware and software enables embedded systems to operate accurately and efficiently.

**Types of Processors**

Processors employed in embedded applications are categorized according to their operational features and intended usage. Common categories include microprocessors, microcontrollers, Digital Signal Processors (DSPs), and Application-Specific Integrated Circuits (ASICs).

A microprocessor represents a single-chip central processing unit responsible for logical and arithmetic computations. These processors are widely utilized in computer-based systems designed for general applications. In comparison, a microcontroller integrates the processor, memory modules, and input/output interfaces within one compact chip, which makes it highly suitable for embedded products. Digital Signal Processors are specially optimized for rapid mathematical calculations and are frequently applied in audio, image, and video signal processing tasks. ASICs are custom-fabricated integrated circuits produced for dedicated applications, offering improved operational speed and higher efficiency levels.

**Memory Architecture (Harvard vs Von-Neumann)**

Memory architecture in embedded systems determines the method through which instructions and data are organized and accessed. Two major architectures commonly implemented are Harvard architecture and Von-Neumann architecture.

Harvard architecture utilizes separate memory sections and independent buses for storing program instructions and data. Because of this arrangement, both can be accessed simultaneously, leading to higher execution speed and better system efficiency. This architecture is extensively adopted in microcontrollers and signal-processing systems where rapid performance is essential.

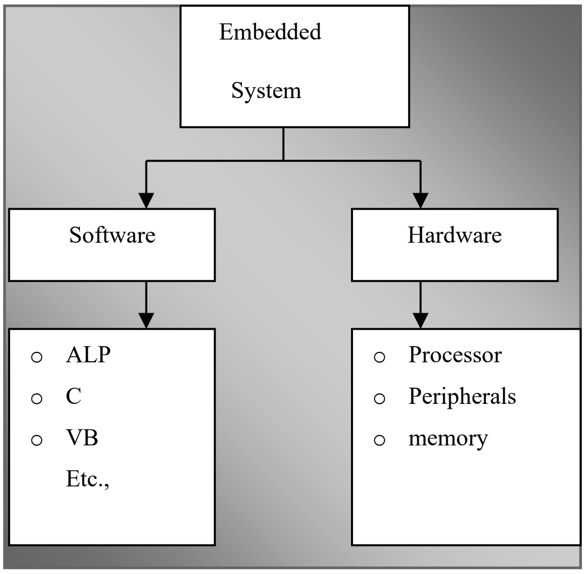



**Figure 7.** Block diagram of embedded system.

On the other hand, Von-Neumann architecture employs a shared memory region for both instructions and data with a common communication bus. This structure offers simpler implementation and greater flexibility; however, simultaneous access is not possible, which may reduce operational speed. Even with this limitation, Von-Neumann architecture remains popular in general-purpose computing devices because of its straightforward design and economical implementation.

## LIST OF COMPONENTS USED

The proposed automatic coolant control system for CNC machines is developed using a combination of electronic and mechanical components. Each component plays a vital role in sensing, processing, and 9controlling the cooling mechanism to ensure efficient operation.

### Arduino UNO

The Arduino UNO is a microcontroller-based development board used as the central control unit of the system. It processes input signals from the temperature sensor and controls the output devices such as the relay and water pump. It is easy to program and widely used in embedded system applications.

### Power Supply Unit

The power supply section delivers the electrical energy necessary for operating every component within the system. It transforms incoming AC power into stable DC voltage levels appropriate for the Arduino board, sensing devices, and additional electronic modules.

### LCD Display

The LCD display is used to show real-time information such as temperature readings and system status. It provides a user-friendly interface for monitoring the operation of the cooling system.

### Relay

A relay functions as an electrically controlled switching device that allows low-power signals from the Arduino to manage high-power equipment. In this setup, the relay controls the switching operation of the water pump according to the detected temperature conditions.

### 12V DC Water Pump

The 12V DC water pump is used to circulate coolant fluid to the machining area. It is activated when the temperature exceeds a predefined limit and helps in reducing heat generated during machining.

### MLX90614 Temperature Sensor

The MLX90614 is a non-contact infrared temperature sensor used to measure the temperature of the tool or workpiece. It provides accurate temperature readings to the Arduino, enabling automatic control of the cooling system.

## WORKING OF COOLING SYSTEM

The developed automatic cooling arrangement functions through continuous temperature observation and control. The MLX90614 temperature sensor constantly detects heat levels at the interface between the cutting tool and the work piece during machining activities. The measured information is transferred to the Arduino UNO, where the input values are analyzed and checked against preset temperature limits. Whenever the detected temperature rises beyond the specified range, the Arduino transmits a signal to the relay module, activating the 12V DC water pump. The pump then circulates coolant toward the machining region to decrease heat generation and maintain suitable working conditions. After the temperature falls below the defined limit, the Arduino disables the relay, causing the pump to stop and avoiding excess coolant consumption. This automatic mechanism improves cooling efficiency, conserves energy, and increases both machining quality and tool durability.

## BASICS OF MACHINING COOLANT

Machining coolant refers to a fluid applied during metal cutting operations for lowering temperature, decreasing friction, and improving surface characteristics. Considerable heat develops because of contact between the cutting tool and the work material during machining processes. Coolants assist in removing this heat, thereby reducing tool damage and preserving dimensional precision. Apart from cooling action, these fluids also offer lubrication, remove metal chips, and prevent corrosion on machined components. Choosing an appropriate coolant and applying it correctly significantly influence machining efficiency and tool service life.

**Types of Coolants**

Machining coolants are categorized according to their composition and operational use. Water-based coolants are commonly preferred because of their strong heat absorption capability and economical nature. Oil-based coolants provide excellent lubrication and are suitable for operations demanding superior surface quality. Synthetic and semi-synthetic coolants combine the benefits associated with both water and oil-based fluids, resulting in enhanced cooling and lubricating performance. Furthermore, Minimum Quantity Lubrication (MQL) systems utilize a limited quantity of lubricant combined with compressed air, thereby lowering coolant usage and reducing environmental effects.

## BLOCK DIAGRAM OF THE SYSTEM

The block diagram of the proposed arrangement illustrates the overall configuration and relationship among various system components. Major sections include the temperature sensor, Arduino UNO, relay module, power unit, LCD display, and water pump. The temperature sensor serves as the input component by transmitting real-time measurements to the Arduino. The Arduino interprets these values and regulates the relay operation according to predefined conditions. Subsequently, the relay controls the water pump, which delivers coolant to the machining region. The LCD screen provides live system information to the operator, including temperature readings and operational status. This diagram demonstrates the transfer of data and control signals throughout the system.

## HARDWARE REQUIREMENTS

The hardware components required for implementing the proposed system include Arduino UNO, MLX90614 temperature sensor, relay module, 12V DC water pump, LCD display, and a regulated power supply unit. Additional components such as connecting wires, resistors, and a breadboard may also be used for circuit assembly. These components collectively enable sensing, processing, and actuation functions necessary for the automatic cooling system.

## SOFTWARE REQUIREMENTS

The software requirements for this setup include the Arduino Integrated Development Environment (IDE), which is employed for writing, compiling, and transferring programs into the Arduino UNO board. The coding is generally developed using Embedded C or Arduino programming language. The software contains instructions for collecting temperature values from the sensor, evaluating them against threshold settings, and controlling relay operation accordingly. Additional programming commands manage the information displayed on the LCD module. Proper software development ensures dependable control, precise operation, and effective cooling system performance.

## DESIGN OF MULTI-LEVEL COOLING SYSTEM

The multi-level cooling system is designed to regulate coolant flow based on different temperature ranges, ensuring efficient and optimized cooling during machining operations. Instead of a simple ON/OFF mechanism, the system operates at multiple levels depending on the temperature measured by the MLX90614 sensor. At lower temperature ranges, the system remains inactive to conserve energy and coolant. As the temperature increases beyond the first threshold, the cooling system is activated at a low level. If the temperature continues to rise, higher levels of cooling are applied by increasing the pump operation or duration. This gradual control mechanism prevents sudden thermal shocks, reduces coolant wastage, and enhances overall machining efficiency. The multi-level approach provides better thermal management compared to conventional systems.

**Applications**

It is primarily suitable for CNC machines such as milling, turning, and drilling machines where temperature control is critical. The system can also be applied in automotive industries, aerospace manufacturing, metal fabrication units, and small-scale workshops. Additionally, it is useful in automated production lines and smart manufacturing environments where energy efficiency and process optimization are important.

**Advantages of Proposed System**

The developed system provides several benefits compared with conventional coolant arrangements. It minimizes unnecessary coolant utilization by operating only under required conditions, thereby reducing wastage and environmental pollution. The system increases tool lifespan by maintaining suitable temperature ranges and also improves surface quality along with product accuracy. It offers energy-saving performance, economical implementation, and simplified installation through the use of embedded components. Automation decreases manual involvement and delivers reliable operational consistency. Moreover, the arrangement can be expanded further and integrated with modern technologies such as IoT for remote supervision and control functions.

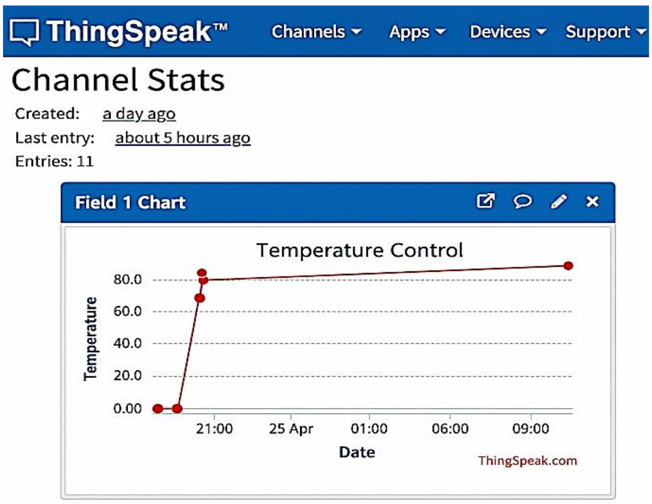
## RESULTS

The proposed automatic coolant control system was successfully designed and implemented using an Arduino UNO, MLX90614 temperature sensor, relay module, and 12V DC water pump. The system was tested under different temperature conditions to evaluate its performance in controlling coolant flow during machining operations.

Experimental observations showed that the system effectively monitored the temperature in real time and activated the coolant pump when the temperature exceeded the predefined threshold values. As the temperature increased further, the multi-level cooling mechanism responded accordingly by maintaining continuous coolant flow, ensuring efficient heat dissipation. When the temperature dropped below the set limit, the system automatically turned off the pump, thereby conserving coolant and energy.

The tool temperature was maintained within safe operating limits, which contributed to enhanced tool life and improved surface finish of the work piece. Additionally, coolant wastage was reduced due to the automated control mechanism, making the system more efficient and environmentally friendly (Figure 8).

Overall, the system exhibited reliable performance, accurate temperature sensing, and effective control of coolant flow. The obtained outcomes confirm the capability of the proposed system to enhance machining performance while promoting environmentally sustainable manufacturing methods.



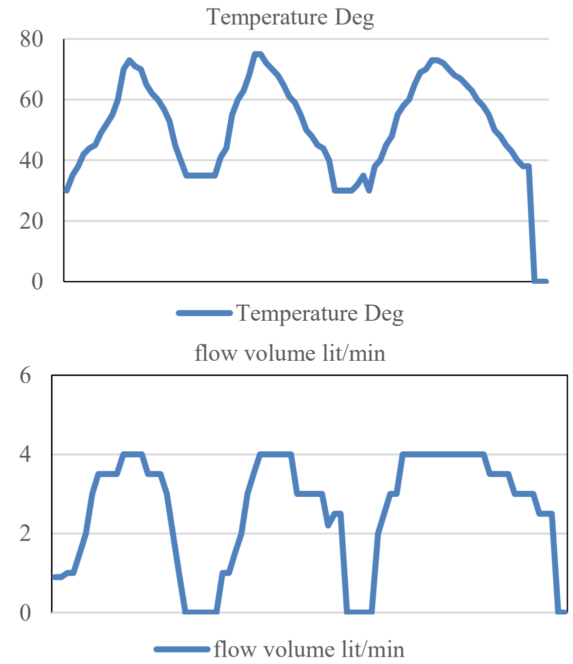



**Figure 8.** Over all stats when machine is in running, showing temperature and flow rates.

## CONCLUSION

This study discussed the development and implementation of an automated coolant regulation system for CNC machines using an embedded-based architecture. The system effectively monitors temperature in real time and controls coolant flow based on predefined conditions. By integrating a non-contact temperature sensor with a microcontroller-based control unit, the system ensures efficient cooling, reduced energy consumption, and improved machining performance. The results demonstrate that the proposed system enhances tool life, improves surface quality, and reduces coolant wastage. Hence, it serves as a practical and cost-effective solution for modern manufacturing industries.

### Future Scope

The developed system can be upgraded further through the integration of modern technologies such as the Internet of Things (IoT) for distant supervision and operational control. Future advancements may also involve incorporating sophisticated sensing devices to achieve improved temperature detection and vibration monitoring accuracy. The system can also be upgraded with adaptive control algorithms and machine learning techniques to predict temperature variations and optimize coolant usage. Additionally, integration with cloud-based systems can enable data logging, predictive maintenance, and real-time performance analysis, making the system more intelligent and efficient.

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