**Jurnal Polimesin**
Department of Mechanical Engineering
State Polytechnic of Lhokseumawe
http://e-jurnal.pnl.ac.id/polimesin

| | | | | | |
|---|---|---|---|---|---|
| e-ISSN | : 2549-1999 | No. | : 5 | Month | : October |
| p-ISSN | : 1693-5462 | Volume | : 23 | Year | : 2025 |

Processing dates: received on 2025-6-02, reviewed on 2025-08-12, accepted on 2025-09-08 and online availability on 2025-10-30

# Development of an embedded coolant system incorporating minimum quantity lubrication for CNC milling applications

**Yogi Muldani Hendrawan**[*]**, Andri Pratama, Taufik Abdul Karim Ihsyani, Ruswandi, Herman Budi Harja**
Department of Manufacturing Engineering Technology, Politeknik Manufaktur Bandung, Kota Bandung 40135, Indonesia
*Corresponding author: yogi@polman-bandung.ac.id

## Abstract

Machinery applications often generate excessive heat due to friction between cutting tools and work-piece materials. To mitigate heat and friction, the use of coolant is necessary in machining operations. Wet coolant systems risk environmental and health concerns because of their consumption rates and chemical content whose waste requires recycling, a process that consumes additional energy and contributes to increased carbon emissions. As a sustainable alternative, the Minimum Quantity Lubrication (MQL) method supplies a fine mist of lubricant in minimal volumes, thereby reducing waste while enhancing machining performance. This study aims to develop an Embedded Coolant System (ECS) based on the MQL method for CNC milling machines, ensuring both ease of integration and effective cooling performance. The ECS was designed with a simplified open-loop controller using an Arduino Mega 2560, a peristaltic pump, and air-pressure control to regulate the coolant mist. Initial calibration was conducted to establish the coolant flow-rate equation as a function of motor speed. Experimental validation was carried out using aluminum and ST-37 steel with HSS and carbide tools, comparing conventional Air-Pressure Cooling (APC) and the proposed MQL-ECS. The results demonstrate that the MQL-ECS significantly reduces machining temperatures and improves surface roughness compared with APC. For aluminum, the average temperature decreased by up to 3% from 30.3°C, while surface roughness improved by 31% from 1.1 µm. For ST-37, the temperature decreased by 5.5% from 31.1°C, and surface roughness improved by 72.74% from 5.96 µm. These findings confirm both the effectiveness and environmental benefits of the proposed system, providing a feasible solution for modern CNC operations.

**Keywords:**
Minimum quantity lubrication, CNC features, coolant system, machining process.

## 1 Introduction

Machining is an important method for producing metal-based products. Machining conditions are typically standardized, particularly with respect to temperature. During the cutting process, temperature increases due to friction between the cutting tool and the work-piece material. Although friction can't be completely eliminated, it can be reduced through the use of a coolant. The cutting process requires energy, which is generated by the relative translational and rotational motion between the cutting tool and the workpiece [1] [2]. As cutting energy increases, both temperature and friction also rise. To maintain temperature and friction within acceptable limits, coolant is applied during machining [3] [4]. This is referred to as wet machining coolant. This method provides stable temperatures, improved surface quality, and increased productivity [5]. The friction generated during the machining process causes overheating at the contact surface between the workpiece material and cutting tools. It is changing material properties, reducing tool life, and increasing the tool wear [6]. It is transferred from the machining area to the out-of-machining system by cutting coolant [7]. It cleans metal chips from the product. Besides the advantages in the machining process, the continuous coolant consumption presents an environmental and health issue.

Most of the cutting coolant consists of a mixture of mineral oil and water [8]. The overconsumption of the cutting coolant causes environmental and health problems, because it consists of phosphor, sulphur, chlorine, and zinc, and causes extra cost [9]. To prevent environmental issues, the used coolant oil needs to be processed. Consequently, carbon emissions will increase.

The other method, Minimum Quantity Lubrication (MQL) or semi-dry machining is a cooling and lubricating approach based on sending a minimal quantity of fluid, which is in the range of approximately 10-100 mL/h in the form of mist into the target zone using pressurized air [10] [11]. MQL coolant method provides many advantages over wet machining, such as gross cost, surface integrity, tool life, power needs, eco-friendliness, neatness, and coolant utilization [12] [13] [14].

According to the many benefits of dry coolant or MQL, there is much research to develop MQL technology for CNC applications. Dhar et al. compare the effect of MQL and wet coolant on cutting temperature, cutting force, and tool wear. The material AISI 9310 is cut by a lathe machine in a designed experimental condition. Surface roughness and dimension error are measured. The experiment results show that MQL reduces cutting temperature, cutting force, and increases tool life. The MQL method shows better performance than wet coolant in terms of surface roughness and dimension error. O. Ozbek and H. Saruhan compare MQL and dry coolant for AISI D2 Steel. Material is cut by a carbide tool which is coated by Chemical Vapor Deposition (CVD) and Physical Vapor Deposition (PVD). This research shows that MQL provides better performance than dry coolant. MQL reduces 23% tool wear, 25% cutting temperature, and 45% cutting tool vibration compared to dry machining, respectively. Surface roughness and tool life performance are increased 89% and 267%, respectively [15]. E. Salur et al chose AISI 1040 steel for the machining experiment to evaluate MQL and dry coolant performance. MQL method provides better machining performance than dry coolant in terms of tool life, cutting temperature, and energy consumption. It reduces 5.5%, 32.5%, and 16.9%, respectively [10]. All of the above studies evaluate tool life, cutting temperature, and energy consumption to validate the advantages of MQL performance.

To achieve the best MQL performance, many researchers implement the Taguchi method to optimize parameters during the machining process [16] [17]. The above method optimizes tool wear and cutting parameters by adjusting machining parameters using the Taguchi method in grinding and turning processes. This method is chosen because it can improves quality with minimal experimental resources and is easy to apply in various applications. Another optimization, the response surface method, is added to provide optimum specific cutting energy and surface roughness. It is achieved by cutting parameters and MQL conditions parametric optimization [18]. Many successful optimization methods have already been implemented in MQL research applications, so they need to be applied in real industrial CNC machine applications.

All the above studies focus on MQL performance by optimizing cutting parameters and MQL conditions. Many material is chosen to validate MQL performance. MQL is evaluated by measuring tool life, cutting temperature, and energy consumption. But to implement the MQL system on an established CNC machine, it has difficulties. Each CNC machine has a different system architecture according to the CNC brand. In order to implement the MQL system easily and user-friendly, this study is proposed. The proposed method is simplified by a simple controller design and simple optimization. It is called The MQL Embedded Coolant System (MQL-ECS).

The rest of this paper is: section 2 gives a brief description of the research method of MQL-ECS. It consists of the embedded coolant system design, proposed controller design, electrical installation architecture, and the work flow of ECS. The proposed method is evaluated by defining an experiment scenario that is described in section 3. It provides an experiment scenario, experiment result, and discussion. It is followed by concluding remarks in section 4.

## 2 Research Method of ECS

To provide a sustainable solution for controlling temperature and friction during the machining process without generating ecological issues, the MQL method is proposed. It is implemented using an embedded control system to enable easy integration into an industrial CNC machine. The MQL method is a coolant technique that combines a minimal volume of oil with compressed air. The mixture is sprayed onto the cutting tool and work-piece to maintain machining temperature and friction within acceptable limits. The small amount of oil evaporates during the cutting process, thereby preventing the production of liquid coolant pollutants. The proposed method can be easily embedded into industrial CNC machines, and the control system is designed for application across various CNC machine tools, making it suitable for a wide range of industrial applications. The proposed method is called MQL-ECS.

The MQL-ECS guarantees that the machining temperature does not reach the maximum temperature in the CNC machine system. It can be attached and integrated into any commercial CNC controller. Fig. 1 shows the embedded coolant system scheme; it is embedded in the CNC machine system. The ECS controller sends commands to the stepper motor driver and air pressure control by considering the minimum coolant oil consumption. The stepper motor driver rotates the stepper motor with an oil peristaltic pump. It pumps coolant oil from the oil supply to the ECS nozzle. It sprays oil coolant with definitive air pressure to the work piece to reduce temperature. All of the coolant parameters are displayed in the ECS LCD.

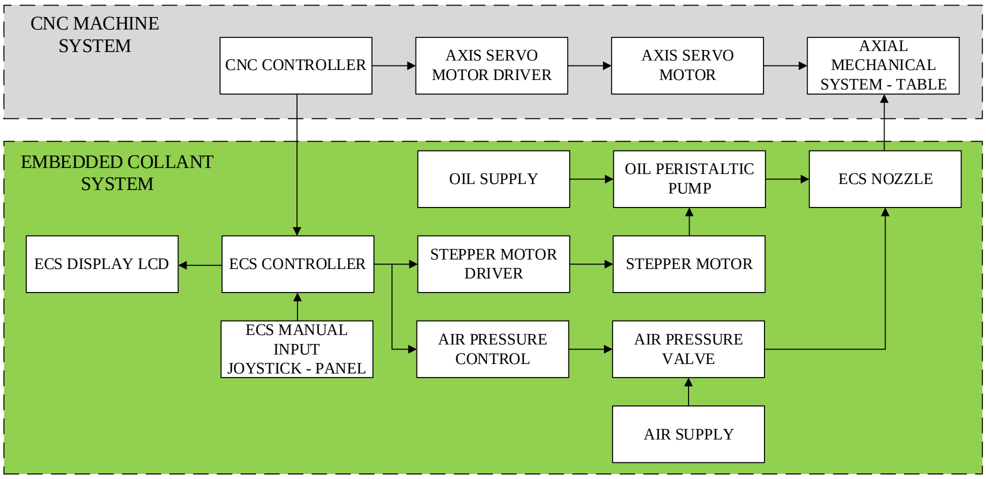


Fig. 1. Embedded coolant system schema.

The proposed controller of ECS uses an open-loop controller as shown in Fig. 2. The reference input is the current input and the defined pressure.

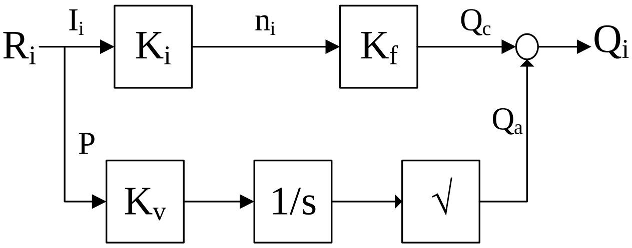


Fig. 2. ECS open loop controller.

The output of ECS controller is the mixed oil coolant flow rate $Q_i$, which is calculated using the Eq. (1), where $Q_i$, $Q_c$, and $Q_a$ are the mixed oil coolant flow rate, oil coolant flow rate, and air flow rate.

$$Q_i = Q_c + Q_a, \tag{1}$$

The mixed oil coolant flow rate is combined between the oil coolant flow rate $Q_c$ and the air flow rate $Q_a$. Both oil coolant flow rate $Q_c$ and air flow rate $Q_a$ depend on a reference input, especially current input $I_i$ and pressure. To estimate both themes, the Eq. (2) – Eq. (5) are derived.

$$Q_c = n_i K_f, \tag{2}$$

$$n_i = I_i K_i, \tag{3}$$

and

$$Q_a = \sqrt{\frac{PK_v}{S}}, \tag{4}$$

where

$$R_i = [I_i \quad P] \tag{5}$$

Where $R_i$, $I_i$, $P$, $K_v$, $S$, $K_i$, $n_i$, and $K_f$ are reference input, current input, pressure input, fluid flow factor, specific gravity of the fluid, current gain, rpm/motor velocity, and flow rate gain. Eq. (2), Eq. (3), and Eq. (4) substitute for Eq. (1) to obtain Eq. (6).

$$Q_i(I_i, P) = I_i K_i K_f + \sqrt{\frac{PK_v}{S}}. \tag{6}$$

To implement the ECS schematic (Fig. 1) and ECS controller design (Fig. 2), ECS installation architecture and system installation are designed as shown in Fig. (3) and Fig. (4), respectively.

The workflow ECS is programmed in the C-programming language to be implemented in the Arduino Mega 2560 controller. It is developed based on workflow ECS algorithms, as shown in Fig. 5. The system will show a flashing page and main menu in the LCD display when it turns on. The flow rate value is defined by inputting to the system between 25 to 85 ml/h. Before it runs, the driver motor L298N and stepper motor are checked; if ready, the system will stand by to execute a coolant command. The command has 3 alternatives: there are “on” button on main controller, the CNC command, and the spindle rotation status.

If one of them is active, it triggers the solenoid valve and stepper motor run. The solenoid valve opens the pressure air, and the stepper motor rotates the peristaltic mechanisms to pump oil coolant from the coolant tank to the nozzle, respectively. Both air pressure and oil coolant are mixed to become mist coolant, which is sprayed by a nozzle onto the material. It runs until the "off" button is pressed, the "stop" command, or the spindle rotation stop. By the proposed mechanism, the cutting temperature is controlled by minimum oil coolant consumption.

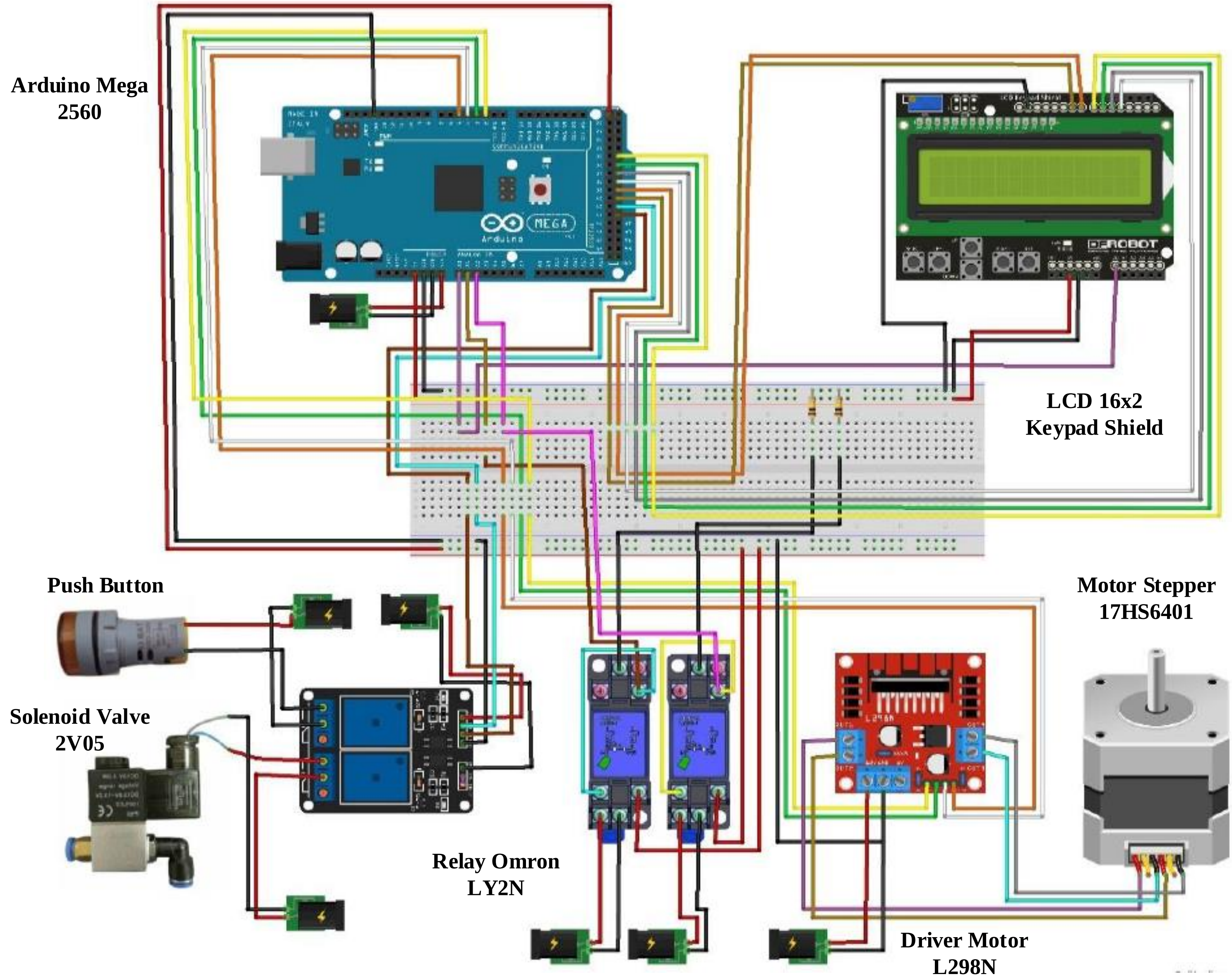
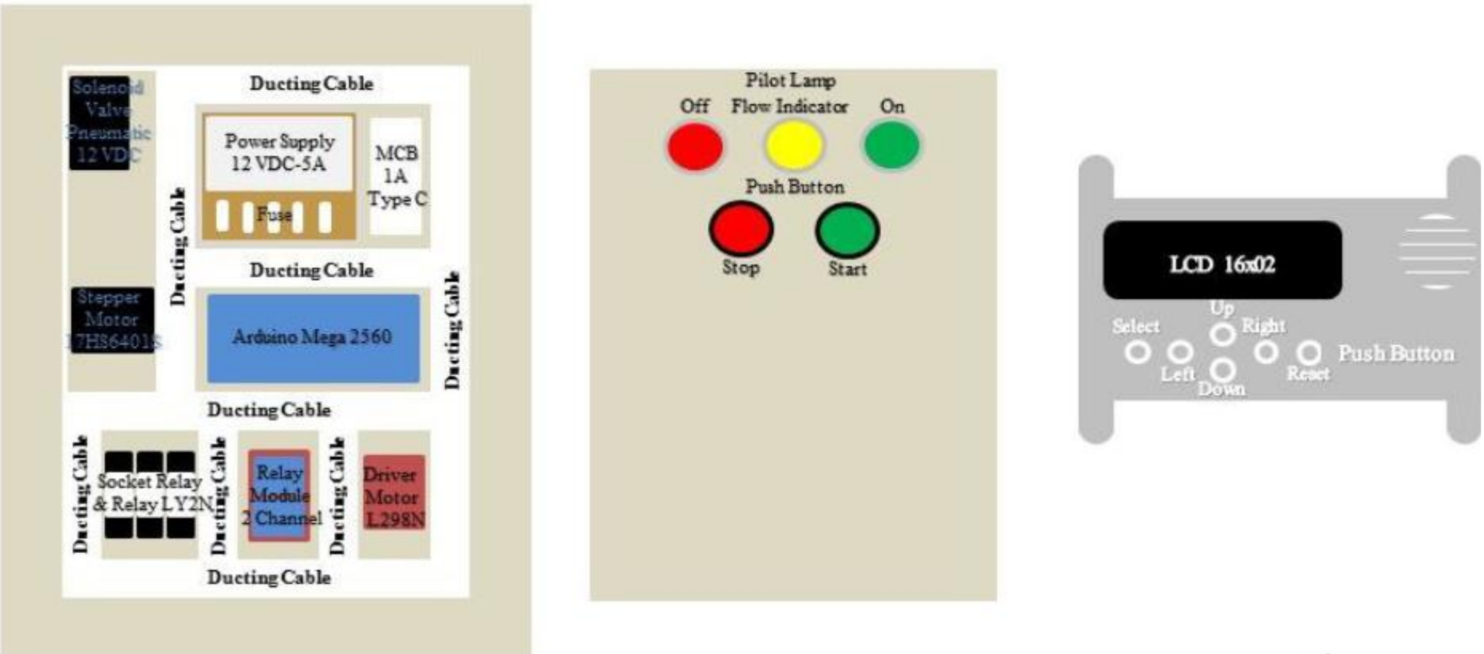


Fig. 3. ECS electrical installation architecture.



ECS component lay out

ECS Panel lay out

ECS LCD Display & Control

Fig. 4. ECS system installation.

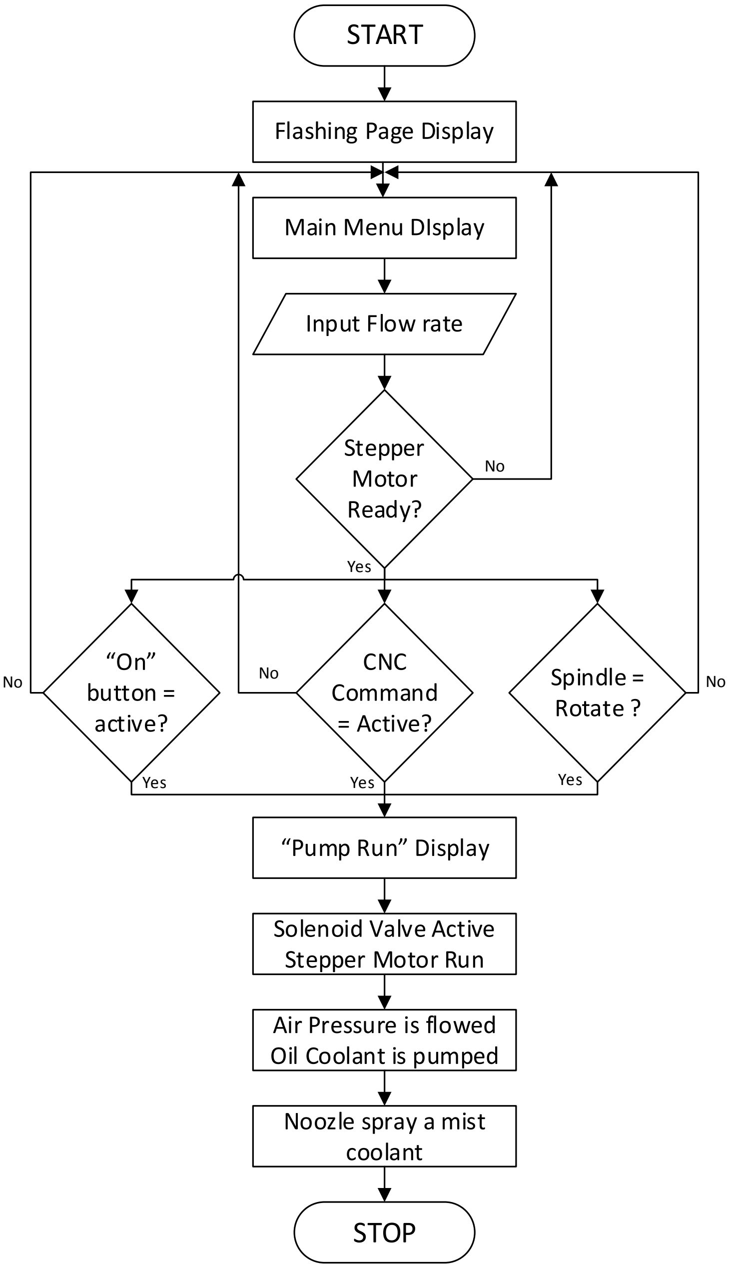


Fig. 5. The workflow ECS algorithm.

Based on the ECS algorithm, the ECS provides a proper basic feature ECS function, such as running an actuator by an input device. To ensure the ECS generates a true coolant flow rate value based on the rotation of the stepper motor as command input, the unknown parameter in Eq. (6) should be observed by an initial experiment. The stepper motor provides rpm as a command input, so the debit equation is calculated (Eq. (7)).

$$Q_i(n_i, P) = n_i K_f + \sqrt{\frac{PK_v}{S}}. \tag{7}$$

The pressure in the proposed system is fixed, so the final debit equation is as Eq. (8).

$$Q_i(n_i) = n_i K_f + c. \tag{8}$$

where

$$c = \sqrt{\frac{PK_v}{S}}. \tag{9}$$

According to Eq. (8), the proposed system is executed by a defined rpm as the command input. Then the output debit is measured to estimate the flow rate gain. It runs seven times for each rpm parameter.

Table 1 shows the average measured debit result. It runs on six defined rpm parameters.

Table 1. Initial experiment results: actual debit output

| Rotation per minute $n$ (rpm) | Average measured debit $\bar{Q}$ (ml/h) |
|---|---|
| 2 | 22.153 |
| 3 | 34.3 |
| 5 | 49.3 |
| 9 | 75.657 |
| 12 | 88.568 |
| 15 | 97.064 |

The correlation between rotation and debit is shown in Fig. 6. Based on the initial experiment result, both themes have a linear correlation. By the linear equation approach, the debit equation of the proposed prototype MQL is Eq. (10).

$$Q_i(n_i) = 5.7592 n_i + 17.02 \tag{10}$$

Eq. (10) shows that the coolant flow rate gain ($K_f$) is 5.7592 and the air debit factor is 17.02 ml/h. It is implemented in an Arduino controller program to convert rpm as command input to coolant flow rate.

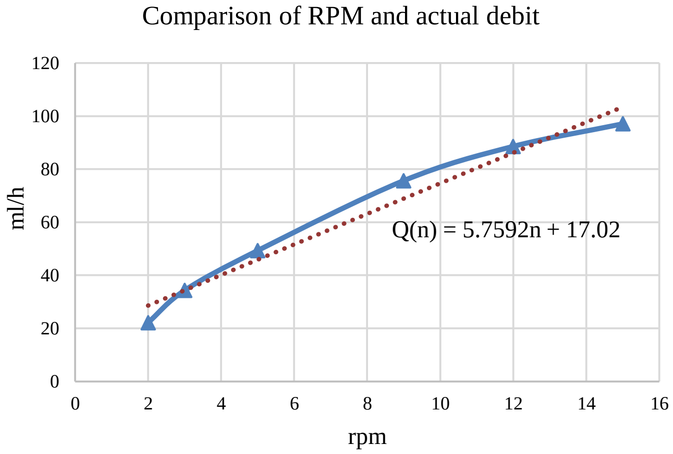


Fig. 6. Graphic of comparison of rpm and actual debit.

## 3 Results and discussion

### 3.1 Experiment scenario

To validate the proposed method, the experiments were conducted on a CNC machine. The ECS system was installed in the CNC machine, as shown in Fig. 7.

Fig. 7. Machining process temperature measurement.

The machining process was carried out on various materials, using different cutting tools and coolant conditions. The cutting process was performed under predefined cutting parameters and combined machining conditions. Temperature was measured during the cutting process, and after machining, the surface roughness of the work-piece was evaluated using a roughness tester to assess surface quality. The results of the proposed method were then compared with the initial method by evaluating the maximum temperature and surface roughness under each cutting condition.

Two materials, aluminum and ST37, are prepared as raw materials. Two cutting tool material types are chosen for cutting material based on the machining condition. There are High Speed Steel (HSS) or Carbide. Two coolant types, Air Pressure Coolant (APC) or MQL, are applied during the machining process to compare both performances.

The experiment is run in 4 conditions: (1) Air pressure coolant, Aluminum, HSS; (2) Air pressure coolant, Aluminum, Carbide; (3) Air pressure coolant, ST37, HSS; (4) Air pressure coolant, ST37, Carbide; (5) MQL, Aluminum, HSS; (6) MQL, Aluminum, Carbide; (7) MQL, ST37, HSS; (7) MQL, ST37, Carbide.

Five linear trajectory cutting experiments are conducted for each experiment scenario. The cutting temperature is measured during the machining process by the thermo-gun as shown in Fig. 7. But the roughness is measured after the machining process by a roughness tester as shown in Fig. 8. The machining process is defined for each experiment scenario as shown in Table 2.

Fig. 8. Surface roughness test.

Table 2. Machining parameter process

| Material | Cutting tool type | | | | | |
|---|---|---|---|---|---|---|
| | HSS | | | Carbide | | |
| | rpm | f mm/min | $D_{oc}$ mm | rpm | f mm/min | $D_{oc}$ mm |
| Al | 3580 | 300 | 0.5 | 3700 | 300 | 0.5 |
| ST 37 | 795 | 300 | 0.5 | 3183 | 300 | 0.5 |

### 3.2 Experiment result

The machining temperature is measured during a material cutting experiment, as shown in Fig. 7. Table 3 shows the experiment results of the aluminum material cutting temperature with 4 experiment scenarios. The APC-HSS provides the maximum machining temperature, 30.3°C, and the minimum machining temperature, 28.1°C is provided by MQL-Carbide. The average machining temperature of APC-HSS, APC-Carbide, MQL-HSS, and MQL-Carbide are 29.52°C, 29.22°C, 28.78°C, and 28.62°C, respectively.

Table 3. Temperature measurement experiment result for aluminum material

| Exp. scenario | Machining temperature (°C) 1 | 2 | 3 | 4 | 5 | Avg |
|---|---|---|---|---|---|---|
| APC-HSS | 29.9 | 29.4 | 28.6 | 30.3 | 29.4 | 29.52 |
| APC-Carbide | 29.3 | 29.3 | 29.4 | 29.3 | 28.8 | 29.22 |
| MQL-HSS | 29.1 | 29 | 28.4 | 28.1 | 29.3 | 28.78 |
| MQL-Carbide | 28.7 | 28.1 | 28.5 | 28.8 | 29 | 28.62 |

Table 4 shows the experimental results of ST-37 material cutting temperature for all experiment scenarios. The APC-HSS provides the maximum machining temperature, 31.1°C. The MQL-Carbide contributes to the minimum machining temperature, 28.3°C. The average machining temperature of APC-HSS, APC-Carbide, MQL-HSS, and MQL-Carbide is 30.64°C, 30.32°C, 28.98°C, and 28.92°C, respectively.

Table 4. Temperature measurement experiment result for ST-37 material

| Exp. scenario | Machining temperature (°C) 1 | 2 | 3 | 4 | 5 | Avg |
|---|---|---|---|---|---|---|
| APC-HSS | 31.1 | 31.1 | 30.4 | 30.3 | 30.3 | 30.64 |
| APC-Carbide | 30 | 30.6 | 30.4 | 30.3 | 30.3 | 30.32 |
| MQL-HSS | 28.3 | 29.4 | 29.4 | 29.1 | 28.7 | 28.98 |
| MQL-Carbide | 28.5 | 28.9 | 28.3 | 28.6 | 30.3 | 28.92 |

Table 5 shows the cutting temperature experiment result comparison of all experiment scenarios for both materials, Aluminum and ST-37. The APC-HSS provides the maximum machining temperature for both materials, 30.3°C and 31.1°C, respectively. Both MQL-HSS and MQL-Carbide contribute the minimum machining temperature for both materials, 28.1°C and 28.3°C, respectively.

Table 5. Temperature measurement experiment result comparison

| Exp. scenario | Machining temperature (°C) | | | | | |
|---|---|---|---|---|---|---|
| | Aluminum | | | ST-37 | | |
| | Min | Max | Avg | Min | Max | Avg |
| APC-HSS | 28.6 | 30.3 | 29.52 | 30.3 | 31.1 | 30.64 |
| APC-Carbide | 28.8 | 29.3 | 29.22 | 30 | 30.6 | 30.32 |
| MQL-HSS | 28.1 | 29.3 | 28.78 | 28.3 | 29.4 | 28.98 |
| MQL-Carbide | 28.1 | 29 | 28.62 | 28.3 | 30.3 | 28.92 |

After the cutting process is done, the surface quality is checked by a surface roughness tester, as shown in Fig. 8. Table 6 shows the experimental results of the surface roughness quality for aluminum material. The APC-Carbide produces the maximum surface roughness of 1.1 µm. The MQL-Carbide contributes the minimum surface roughness of 0.54 µm. The average surface roughness of APC-HSS, APC-Carbide, MQL-HSS, and MQL-Carbide is 0.762 µm, 1.02 µm, 0.704 µm, and 0.78 µm, respectively.

Table 6. Surface roughness measurement experiment result for aluminum material

| Exp. scenario | Surface roughness (µm) 1 | 2 | 3 | 4 | 5 | Avg |
|---|---|---|---|---|---|---|
| APC-HSS | 0.73 | 0.85 | 0.84 | 0.63 | 0.76 | 0.762 |
| APC-Carbide | 0.9 | 1.09 | 1.07 | 0.92 | 1.1 | 1.02 |
| MQL-HSS | 0.76 | 0.69 | 0.77 | 0.59 | 0.71 | 0.704 |
| MQL-Carbide | 0.54 | 0.92 | 0.69 | 0.72 | 1.03 | 0.78 |

Table 7 shows the experimental results of ST-37 material surface roughness with 4 experiment scenarios. The APC-HSS provides the maximum surface roughness of 5.96 µm and the minimum surface roughness of 1.01 µm, which is provided by MQL-Carbide. The average surface roughness of APC-HSS, APC-Carbide, MQL-HSS, and MQL-Carbide is 4.876 µm, 1.81 µm, 3.732 µm, and 1.28 µm, respectively.

Table 7. Surface roughness measurement experiment result for ST-37 material

| Exp. scenario | Surface roughness (µm) 1 | 2 | 3 | 4 | 5 | Avg |
|---|---|---|---|---|---|---|
| APC-HSS | 3.2 | 5.45 | 5.92 | 5.96 | 3.85 | 4.876 |
| APC-Carbide | 2.03 | 1.54 | 1.82 | 2.11 | 1.55 | 1.81 |
| MQL-HSS | 3.06 | 3.61 | 4.67 | 2.53 | 4.79 | 3.732 |
| MQL-Carbide | 1.01 | 1.16 | 1.36 | 1.27 | 1.6 | 1.28 |

Table 8 shows the surface roughness experiment result comparison of all experiment scenarios for both materials, Aluminum and ST-37. The APC-HSS provides the maximum surface roughness for ST-37 material and APC-Carbide for Aluminum material, 5.96 µm and 1.1 µm, respectively. MQL-Carbide contributes the minimum surface roughness for both aluminum and ST-37 material 0.54 µm and 1.01 µm, respectively.

Table 8. Surface roughness measurement experiment result comparison

| Exp. scenario | Surface roughness (µm) | | | | | |
|---|---|---|---|---|---|---|
| | Aluminum | | | ST-37 | | |
| | Min | Max | Avg | Min | Max | Avg |
| APC-HSS | 0.63 | 0.85 | 0.762 | 3.2 | 5.96 | 4.876 |
| APC-Carbide | 0.9 | 1.1 | 1.02 | 1.54 | 2.11 | 1.81 |
| MQL-HSS | 0.59 | 0.77 | 0.704 | 2.53 | 4.79 | 3.732 |
| MQL-Carbide | 0.54 | 1.03 | 0.78 | 1.01 | 1.36 | 1.28 |

### 3.3 Discussion

Fig. 9 shows the comparison of air pressure, coolant and minimum quantity lubrication performances to minimize machining material. In both aluminum and ST-37 materials, the proposed MQL method gives better performance than APC method for all cutting tool cases. In aluminum material, the best performance is 28.1$^o$C, in other terms, maximum and average reduced 2.2$^o$C (7.3%) and 0.9$^o$C (3%), respectively. In the ST-37 case, MQL reduces the maximum temperature from 31.1$^o$C to 28.3$^o$C. It is equal to the maximum and average reduction of 2.8$^o$C (9%) and 1.72$^o$C (5.5%). To conclude MQL performance, the average reduction percentage of MQL is 8.15% from the maximum machining temperature. The MQL maintains a temperature under 30$^o$C, which is the cutting temperature standard. The proposed MQL method provides better performance than the APC method because MQL combines optimum air pressure and minimum lubrication to reduce friction and cutting temperature. The lubricant has a function to absorb friction and heat from the cutting process. It evaporates liquid lubrication into the air. The proposed combination is validated to reduce cutting temperature. It can be implemented in any material because a similar phenomenon occurs in both materials.

Besides temperature, the proposed method also provides surface quality. It is measured by a surface roughness tester. Fig. 10 shows the comparison of air pressure, coolant and minimum quantity lubrication performances to provide surface roughness. In both aluminum and ST-37 materials, the proposed MQL method gives better performance than the APC method for all cutting tool cases. In aluminum material, the best performance is 0.54 µm, in other terms, maximum and average surface roughness differentiation 0.56 µm (51%) and 0.316 (31%), respectively. In the ST-37 case, MQL reduces maximum surface roughness from 5.96 µm to 1.01 µm. It is equal to the maximum and average reduction 4.95$^o$C (83%) and 3.596$^o$C (72.74%). To conclude MQL performance, the average reduction percentage of MQL is 67% from the maximum surface roughness. The proposed MQL method provides better performance than the APC method because the lubricant guarantees the normal cutting condition and reduces friction between material and cutting tools because of its ability to absorb heat from the cutting process. The optimum cutting condition provides surface quality because the optimum cutting process occurred. The proposed combination is validated to increase surface roughness quality by 67%. It can be implemented in any material and cutting tools because a similar effect occurs in all experiment scenarios. The MQL-ECS has been successfully implemented in an industrial CNC machine, demonstrating its effectiveness in reducing the temperature of both the work-piece material and the cutting tool.

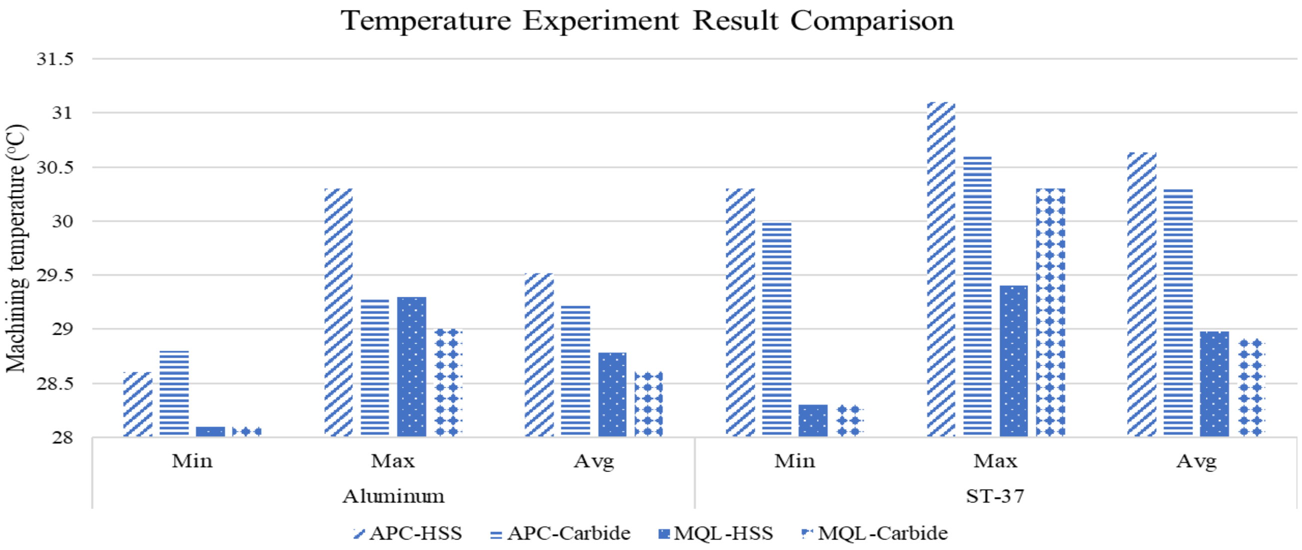


Fig. 9. Graphic of temperature experiment result comparison.

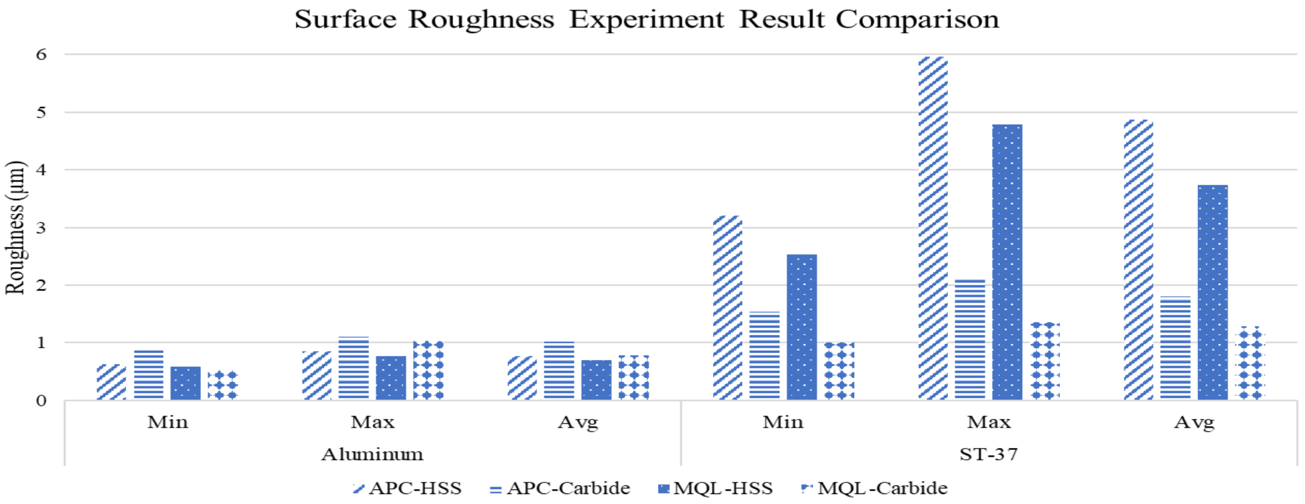


Fig. 10. Graphic of surface roughness experiment result comparison.

## 4 Conclusions

This study successfully developed and validated an ECS utilizing the MQL method for CNC milling machines. The proposed system was designed for easy integration with existing CNC controllers and implemented using a simple open-loop controller based on Arduino Mega 2560. Through controlled experiments, the system demonstrated effective coolant flow rate control and significant improvements in machining performance.

Experimental results showed that the MQL-based ECS consistently outperformed conventional APC systems in both thermal regulation and surface quality. In aluminium and ST-37 materials, the ECS reduced average machining temperatures by up to 5.5% and improved surface roughness by up to 72.74%. These improvements are attributed to the MQL method's ability to combine optimal air pressure and minimal oil usage, reducing friction and dissipating heat efficiently. Unlike previous studies, in which the working temperature was not regulated, the proposed system effectively maintains temperature control, demonstrating a significant improvement in process stability.

The results validate the ECS as a sustainable alternative to traditional wet cooling systems by maintain temperature. Its modular design and compatibility with various CNC machine architectures make it a promising solution for industrial applications seeking to reduce environmental impact while maintaining machining quality and efficiency.

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