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

e-ISSN	: 2549-1999	No.	: 1	Month	: February
p-ISSN	: 1693-5462	Volume	: 24	Year	: 2026

Processing dates: received on 2025-10-23, reviewed on 2026-01-15, accepted on 2026-02-01 and online availability on 2026-02-28

Design and development of a microcontroller-based automatic wet scrubber system for welding smoke control using CO and gas indicator sensors

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Abstract

Welding workshops are one of the work environments with a high potential for air pollution due to welding smoke containing heavy metal particles and hazardous gases such as Carbon Monoxide (CO). This research aims to design and build a wet scrubber-based welding smoke cleaning device that works automatically using a gas sensor and a microcontroller system. This system consists of an exhaust fan, a diaphragm pump, a drum filter containing activated charcoal and stone, and MQ-2 and MQ-7 sensors that detect smoke**.** The system automatically activates when hazardous gases are detected. System calculations show an air flow rate of 258.84 m^3/hour and a pump water flow rate of 0.00208 m^3/minute. This device was designed with space efficiency, low power consumption (90 W), and ease of maintenance in mind. Each experimental condition was tested for 10 minutes and repeated three times. MQ-2 and MQ-7 sensor readings were recorded at 1-second intervals. The inlet (Cin) and outlet (Cout) values were obtained from the average stabilized sensor readings measured before and after the activation of the wet scrubber system. The experimental results showed that the proposed system achieved relative reductions of up to 19.41% for smoke indicator readings and 17.55% for CO readings at full water flow rate, while reductions of 13.69% (smoke) and 15.28% (CO) were observed at half water flow rate. These results are based on sensor-based relative measurements and indicate the practical performance of the prototype system. This research is expected to provide a practical solution for maintaining air quality in small to medium-scale welding workshops.

Keywords:
Wet scrubber, welding, air purifier, automatic sensor, exhaust fan, air pollutant.

1 Introduction

Clean air is essential for human health and productivity. Chronic exposure to polluted air has significant health impacts, ranging from respiratory disorders and chronic obstructive pulmonary disease to an increased risk of cancer. Industrial work environments, particularly welding workshops, pose a high potential risk of exposure to air pollutants. Benchmarking against previous studies, demonstrated that prolonged exposure to airborne asbestos was associated with a significantly increased risk of asbestosis, with a hazard ratio of 2.4 for exposure durations of 15 years or longer, highlighting the critical role of exposure intensity and duration [1].

Various air treatment technologies have been developed to address the problem of ambient air pollution. In general, these technologies can be classified into two main categories: (1) dry filtration systems, which include the use of High Efficiency Particulate Air (HEPA) filters, electrostatic precipitation technology, and adsorption using activated carbon; and (2) wet scrubber systems. Dry filtration systems are effective in filtering particulates, but their dissolved gas removal efficiency is relatively low. In contrast, wet scrubbers offer higher efficiency in absorbing gases and capturing particulates through direct contact between the gas phase and a liquid, typically water or a chemical solution. The selection of the appropriate technology depends on the characteristics of the pollutant and the specific needs of the application [2].

Previous research has explored the development of air purifiers for various industrial applications, including the welding sector. For example, a dual filtration system using a combination of HEPA and activated carbon filters was developed, which was effective for particulate removal but less optimal for gas removal. This system also utilized a local ventilation system, which requires high energy consumption and is less portable. A simple wet scrubber system was shown to reduce particulate concentrations by up to 80%, but further optimization is needed for specific applications in welding workshop environments. Previous research reported that the optimized vortex wet scrubber with dolomite suspension achieved high removal efficiencies, namely 95–98% for PM10, 90–95% for PM2.5, and up to 98% for SO_2 absorption. However, approximately 5–15% of ultrafine carbon particles (<1 μm) were still not captured, and the study did not provide quantitative data on energy consumption or specific energy efficiency. Therefore, a research gap exists in quantitatively evaluating design optimization strategies that simultaneously enhance ultrafine particle capture and reduce energy consumption [3].

Although previous research has demonstrated the technology's potential for reducing air pollutants, it faces several limitations, including large equipment size, high investment and operational costs, and its suitability for confined workspaces such as welding workshops. Integrated research combining wet scrubber technology with energy efficiency considerations are still limited [4].

Wet scrubber systems utilize the principle of direct contact between a polluted gas stream and an absorbent liquid in a spray chamber or wash column. This process causes particles and gases to dissolve or become trapped in the liquid, producing clean air at the outlet. This technology offers the advantages of relatively low operational and maintenance costs, as well as the ability to simultaneously reduce gaseous and particulate pollutants, making it suitable for small-scale industrial applications [5].

Welding processes generate a complex mixture of air pollutants, including gaseous components and particulate matter. Carbon monoxide (CO) is a gaseous pollutant produced by incomplete combustion and shielding gas decomposition, which can cause hypoxia and acute poisoning at elevated concentrations. In contrast, welding fumes primarily consist of fine and ultrafine particulate matter composed of metal oxides such as iron, manganese, and chromium, which are associated with respiratory inflammation and long-term occupational health risks [6].

In this study, the focus is placed on distinguishing between these two pollutant categories. CO is evaluated as a gaseous pollutant using an MQ-7 sensor, while welding fumes are assessed indirectly using an MQ-2 sensor as a relative smoke indicator rather than a quantitative particulate measurement instrument. The health hazards of welding fume particulates are discussed based on established literature, whereas the experimental results of this work are limited to sensor-based relative reductions in CO and smoke indicator readings [7].

Although wet scrubber technology has been widely studied for air pollution control, most previous research has focused on large-scale industrial applications and emphasized particulate removal performance using standard laboratory-based measurement methods. Limited attention has been given to the development of compact wet scrubber systems suitable for confined environments such as welding workshops, particularly those equipped with real-time monitoring and automatic control capabilities. Furthermore, previous studies rarely integrate gas and smoke indicator sensors with microcontroller-based control systems to adapt scrubber operation based on actual pollutant concentration levels. Therefore, this research addresses this gap by developing a microcontroller-based automatic wet scrubber system integrated with CO and gas indicator sensors for welding smoke control, emphasizing practical applicability, energy-efficient operation, and real-time performance evaluation. Therefore, the development and optimization of a wet scrubber-based air purifier for welding workshops is a relevant endeavor worthy of further study [8].

2 Research methods

2.1 Tools and materials

This research used various tools, such as a hand grinder welding machine, exhaust fan machine, diaphragm pump, hand drill machine, meter, elbow, height gouge. The materials used included angle iron, spiral hose, blue plastic drum, pipe, water container, nozzle, stones (filter), charcoal (filter), water, bottle cap, water tap, spray stick, pipe reducer, rivet nails, aluminum plate zinc, and fiber hinge. The MQ-2 and MQ-7 sensors were used as relative gas and smoke indicator sensors rather than absolute measuring instruments. Prior to the experiments, the sensors were preheated according to the manufacturer’s recommendations to ensure stable output signals. The sensor readings were used to observe relative changes in smoke intensity and CO concentration before and after the operation of the wet scrubber. No direct calibration against certified gas analyzers was conducted; therefore, the results are interpreted as relative percentage reductions rather than absolute concentration values [9].

2.2 Collection techniques

In this study, the author used the data collection techniques: observation and literature review.

2.2.1 Observation

Direct observation of air conditions in the welding workshop environment as an initial step to identify real problems that occur in the field. The experiments were conducted in both open and closed workshop environments to evaluate system performance under practical conditions. To ensure consistency, key variables such as the distance between the welding source, wet scrubber inlet, and gas sensors, as well as welding parameters and electrode type, were kept constant. In closed workshop tests, doors and windows were maintained in a consistent condition without additional mechanical ventilation, while open workshop tests were conducted under relatively calm weather conditions. Although minor environmental variations may occur, the results were evaluated based on relative changes in sensor readings before and after scrubber operation. Each experimental condition was tested for 10 minutes and repeated three times. MQ-2 and MQ-7 sensor readings were recorded at 1-second intervals. The inlet (Cin) and outlet (Cout) values were obtained from the average stabilized sensor readings measured before and after the activation of the wet scrubber system [10].

2.2.2 Literature review

Through simulations of the design and construction of these tools obtained from final project sources, theses, journals, books and websites as a reference for the author to solve problems and prepare the final assignment.

2.3 Calculation system

2.3.1 Air flow rate

According to Budianto et al., (2024), air discharge can be calculated using the Eq. (1), where Q is air flow rate (m³/s), A is channel cross-sectional area (m²) and V is air flow velocity from the exhaust fan (m/s).

$$Q = A \times V \tag{1}$$

2.3.2 Pump water flow

According to Ghasypham (2023), the pump water discharge can be calculated using the Eq. (2), where Qw is water flow rate (m³/s), v is water volume (liters), and t is time (seconds).

$$Qw = v/t \tag{2}$$

2.3.3 Pollutant reduction based on sensor readings

In this study, the pollutant reduction efficiency was evaluated based on relative sensor readings obtained from MQ-2 and MQ-7 sensors. Since these sensors do not provide direct measurements in absolute concentration units (e.g., μg/m³), the inlet (Cin) and outlet (Cout) values were defined as the average stabilized sensor output values recorded before and after wet scrubber operation [11].

The relative reduction efficiency was calculated using the Eq. (3), where Cin is average sensor reading before wet scrubber operation (dimensionless unit), Cout is average sensor reading after wet scrubber operation (dimensionless unit) and η is relative reduction efficiency (%).

$$\eta = ((Cin - Cout) / Cin) \times 100\% \tag{3}$$

The wet scrubber system consists of an exhaust fan, a spray-based scrubbing chamber, and a filter drum integrated with an automatic control unit. Polluted air generated from the welding process is drawn by the exhaust fan into the scrubber inlet and flows upward through the drum before exiting through the outlet at the top [12].

Water is supplied by a diaphragm pump and sprayed into the chamber using a single low-pressure conical spray nozzle installed at the upper section of the drum. The gas–liquid contact occurs in the central region of the drum, where upward-flowing polluted air interacts with downward-falling water droplets, enabling pollutant capture through inertial impaction and gas absorption [13].

Above the spray zone, a multilayer filter media arrangement is installed, consisting of stones (gravel) as a mechanical filter layer and activated carbon as an adsorption layer for residual gaseous pollutants. The treated air then exits the system, while used water is collected at the bottom of the drum and discharged periodically [14].

Routine maintenance includes inspection of the nozzle to prevent clogging, periodic replacement or cleaning of stone filters, replacement of activated carbon, and drainage of contaminated water to maintain stable system performance [15].

2.4 Steps for implementing research

2.4.1 Problem identification

The initial stage for researchers before starting a design is to identify problems in the field. Researchers try to identify existing issues in their environment that could potentially be addressed in a research project.

2.4.2 Literature study

Next, they conduct a literature study, such as searching for data on smoke purifiers. For example, they should identify the advantages and disadvantages of the machine, which will serve as references in the research process. This literature study includes reading previous reports in the library, searching for research journals on websites, and watching videos of machine experiments on YouTube as references for problem-solving [16].

2.4.3 Design concept

Create a smoke purifier design for a welding workshop by drawing the design in Autodesk Inventor. Then, they begin by selecting the type of material to be used for each component of the shredder [17].

2.4.4 Design concept analysis

Selecting the most appropriate design to meet the needs of the smoke purifier in the welding workshop.

2.4.5 Tool design and manufacture

Assembling parts into a machine component through the manufacturing process.

2.4.6 Functional testing

After tool assembly is complete, we will of course conduct a functional test to determine whether the tool we built is functioning properly or whether any repairs are still needed during assembly. The indicator for this tool functional test is that it is considered successful if the testing process produces clean air in the welding workshop environment. Functional testing is a process of testing the tool, which includes determining whether the tool's components are functioning according to their intended purpose [18].

2.4.7 Sensor placement

The MQ-2 (smoke indicator) and MQ-7 (CO) sensors were positioned at a fixed distance of approximately 30 cm from the welding source, near the air inlet of the wet scrubber system, to represent inlet pollutant conditions (Cin). Outlet measurements (Cout) were obtained by placing the sensors at the air outlet of the scrubber, approximately 20 cm downstream from the exhaust outlet, ensuring that the measured air had fully passed through the scrubbing chamber. Sensor positions were kept constant for all tests to ensure data consistency [19].

2.4.8 Enclosure conditions

Experiments were conducted in both closed and semi-open workshop environments to represent practical welding conditions. In closed-room tests, doors and windows were kept closed and no additional mechanical ventilation was used. In semi-open tests, experiments were performed under relatively calm ambient conditions with minimal wind disturbance. No external airflow control system was applied; therefore, results are interpreted based on relative changes in sensor readings rather than absolute concentration values [20].

2.4.9 Welding duration and type

Welding smoke was generated using a manual metal arc welding (SMAW) process with standard mild steel electrodes. Each experimental run involved continuous welding for 10 minutes, ensuring sufficient pollutant generation and stable sensor response [21].

2.4.10 Number of repeats

Each experimental condition (full water flow rate and half water flow rate) was repeated three times. Sensor data were recorded at 1-second intervals, and the reported values represent averaged results from repeated trials [22].

2.4.11 Baseline stabilization time

Prior to each test, the MQ-2 and MQ-7 sensors were powered on and allowed to preheat and stabilize for approximately 3–5 minutes, following manufacturer recommendations. Baseline (Cin) values were calculated from the average stabilized sensor readings recorded immediately before the activation of the wet scrubber system [23].

2.4.12 Threshold values for fan and pump activation

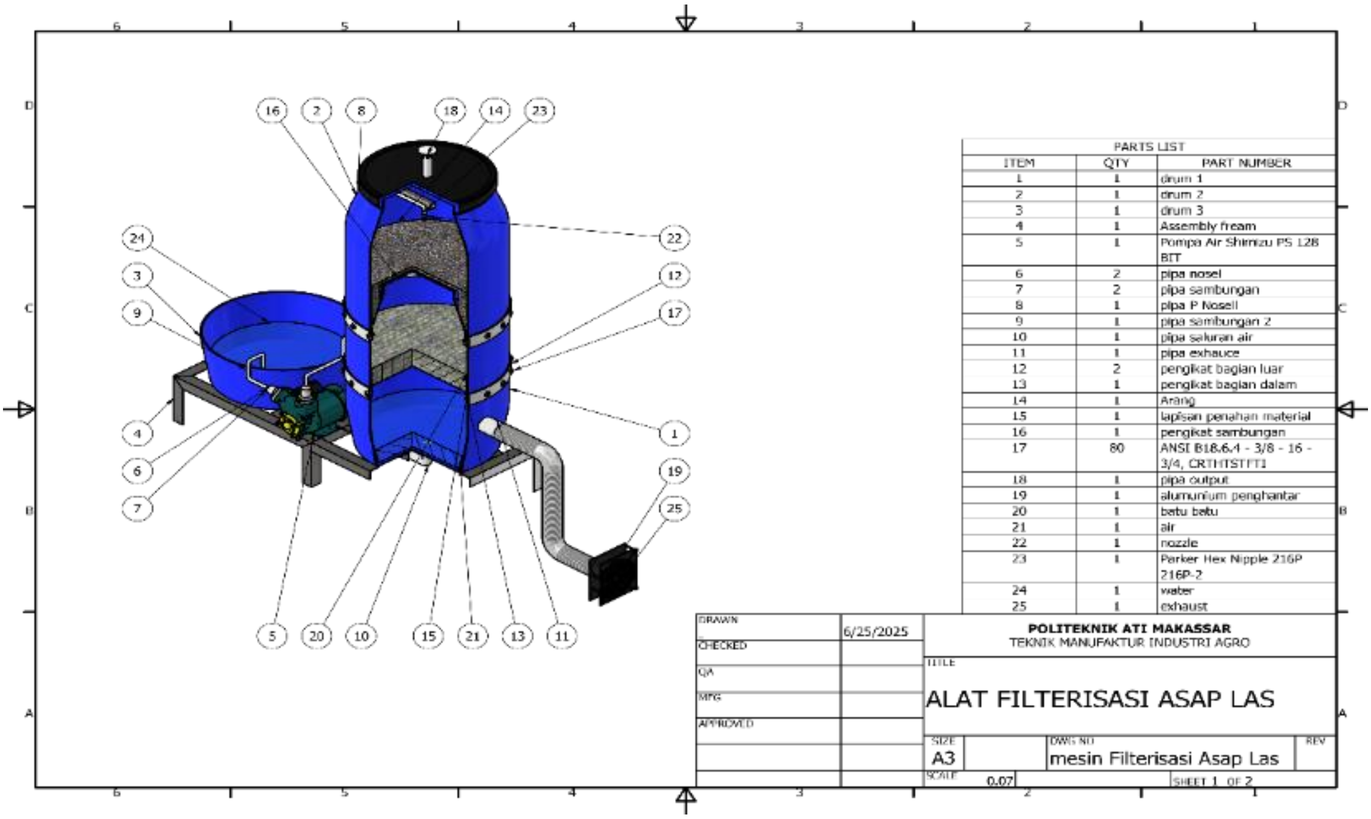
The wet scrubber system was controlled automatically using an Arduino microcontroller. The exhaust fan and water pump were activated when sensor readings exceeded predefined threshold values. These thresholds were determined experimentally based on stable baseline conditions and noticeable increases in sensor output during welding activity. Once the sensor readings fell below the threshold level, the system returned to standby mode. The threshold values were used as relative trigger points, not as regulatory concentration limits [24].

3 Results and discussion

3.1 Results

3.1.1 Tool design drawing results

Tool design drawings are the initial stage in creating a design. Machine construction refers to the engineering drawings that have been designed. The Fig.1 is an explanation of the components of the designed tool.



PARTS LIST

ITEM	QTY	PART NUMBER
1	1	drum 1
2	1	drum 2
3	1	drum 3
4	1	Assembly fream
5	1	Pompa Air Shimizu PS 128 BIT
6	2	pipa nosel
7	2	pipa sambungan
8	1	pipa P Nosell
9	1	pipa sambungan 2
10	1	pipa saluran air
11	1	pipa exhauce
12	2	pengikat bagian luar
13	1	pengikat bagian dalam
14	1	Arang
15	1	lapisan penahan material
16	1	pengikat sambungan
17	80	ANSI B18.6.4 - 3/8 - 16 - 3/4, CRTHTSTFT1
18	1	pipa output
19	1	alumunium penghantar
20	1	batu batu
21	1	air
22	1	nozzle
23	1	Parker Hex Nipple 216P 216P-2
24	1	water
25	1	exhaust

DRAWN 6/25/2025
CHECKED
QA
MFG
APPROVED

POLITEKNIK ATI MAKASSAR
TEKNIK MANUFAKTUR INDUSTRI AGRO

TITLE
ALAT FILTERISASI ASAP LAS

SIZE A3
DWG NO mesin Filterisasi Asap Las
REV
SCALE 0.07
SHEET 1 OF 2

Fig. 1. Design drawing of the smoke purifier.

3.1.2 Test results

Based on testing in the welding workshop and data analysis that has been carried out, the research results were obtained. Each experimental condition was repeated three times (n = 3). For each trial, sensor readings were recorded at 1-second intervals and averaged to obtain representative inlet (Cin) and outlet (Cout) values. Due to data logging limitations, only averaged reduction percentages are reported in this study. Statistical dispersion analysis (mean ± SD) is planned for future work using dedicated data acquisition and storage (Table 1).

3.1.3 Tables and graphs data processing results

Tables and graphs data processing results on particle removal efficiency as shown in Fig. 2-Fig. 5 and Table 2-Table 3.

Table 1. Testing in the welding workshop and data analysis

Testing	Result
Air flow rate	258.84 m^3/ hour
Pump water flow half water tap opening measurement	0.11736 m^3/ hour
Pump water flow full water tap opening measurement	0.12456 m^3/ hour
MQ-7, full water flow (%)	17.55%
MQ-7, half water flow (%)	15.28%
MQ2 particle removal efficiency performance fully opening the water tap	19.41%
MQ2 particle removal efficiency performance halfway opening the water tap	13.69%

Table 2. The valve opening angle was set to 45°

MQ-7 CO 45°				MQ-2 smoke 45°			
No.	CO input (µg/m^3)	CO output (µg/m^3)	Efficiency (%)	No.	Smoke input (µg/m^3)	Smoke output (µg/m^3)	Efficiency (%)
1	96452351.87	23593729.15	75.54%	1	145491.6155	35399.1411	75.67%
2	103871763.6	26709882.06	74.39%	2	153510.8384	37461.22699	75.60%
3	99420116.55	25151805.6	74.70%	3	144346.0123	37461.22699	74.05%
4	93484587.2	23816311.5	74.52%	4	137472.3926	35742.82209	74.00%
5	92742646.03	23148564.45	75.04%	5	150074.0286	35399.1411	76.41%
6	96452351.87	24261476.2	74.85%	6	140909.2025	36430.18405	74.15%
7	92742646.03	25596970.31	72.40%	7	142054.8057	38492.26994	72.90%
8	98678175.38	26042135.01	73.61%	8	153510.8384	39179.6319	74.48%
9	99420116.55	25819552.66	74.03%	9	152365.2352	38492.26994	74.74%
10	94968469.54	25151805.6	73.52%	10	147782.8221	38492.26994	73.95%
Average	96823322.46	24929223.25	74.25%	Average	146751.7791	29183.09775	80.11%

Table 3. The valve opening angle was set to 90°

MQ-7 CO 90°				MQ-2 smoke 90°			
No.	CO input (µg/m^3)	CO output (µg/m^3)	Efficiency (%)	No.	Smoke input (µg/m^3)	Smoke output (µg/m^3)	Efficiency (%)
1	93484587.2	19702247.72	78.92%	1	151219.6319	29883.06135	80.24%
2	94226528.37	18656110.68	80.20%	2	150074.0286	28806.19427	80.81%
3	97194293.04	19702247.72	79.73%	3	161530.0613	30421.49489	81.17%
4	98678175.38	19004823.03	80.74%	4	183296.5235	29344.62781	83.99%
5	1001622057.7	19702247.72	80.33%	5	167258.0777	30421.49489	81.81%
6	86807116.69	18481754.5	78.71%	6	136326.7894	27460.11043	79.86%
7	89774881.36	18481754.5	79.41%	7	143200.409	28267.76074	80.26%
8	100162057.7	19702247.72	80.33%	8	152365.2352	29075.41104	80.92%
9	94968469.54	18656110.68	80.36%	9	147782.8221	28536.97751	80.69%
10	89774881.36	18830466.85	79.02%	10	147782.8221	28267.76074	80.87%
Average	94523304.84	19092001.11	79.78%	Average	154083.6401	29048.48937	81.15%

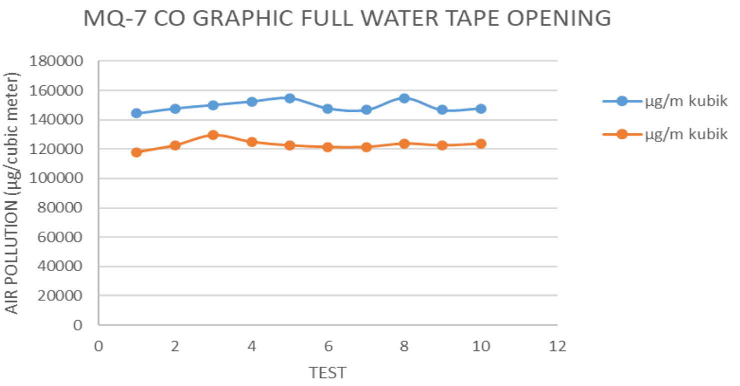


Fig. 2. MQ-7 CO graphic full water tape opening.

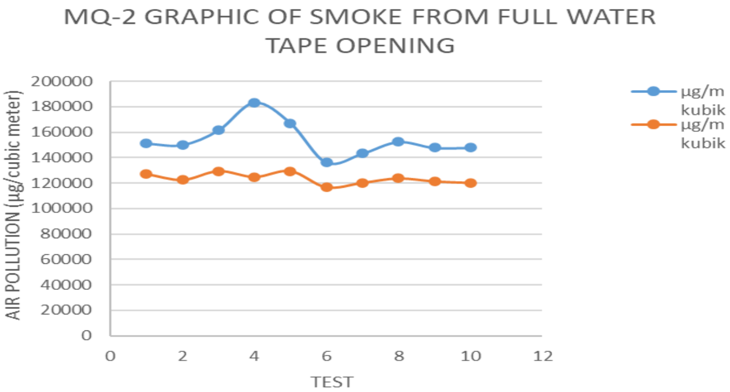


Fig. 3. MQ-2 graphic of smoke from water take opening.

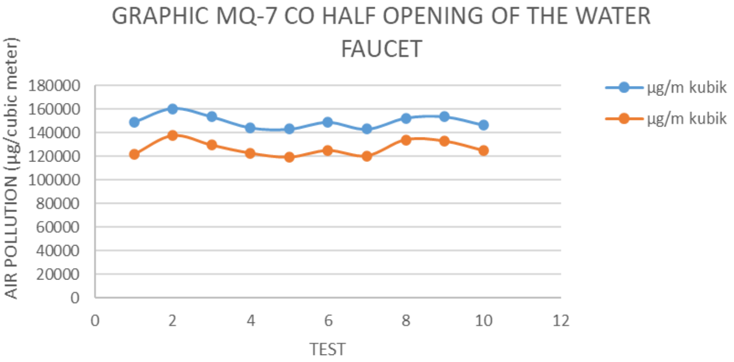


Fig. 4. Graphic MQ-7 CO half opening of the water faucet.

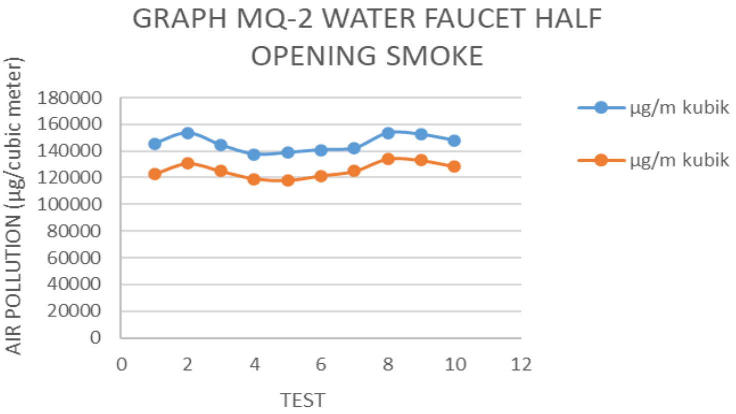


Fig. 5. Graphic MQ-2 water faucet half opening smoke.

3.2 Discussion

This study aimed to assess the performance of an automatic wet scrubber in reducing CO and smoke levels in a workshop area used for welding. An MQ-2 sensor was used as a relative smoke/gas indicator, while an MQ-7 sensor was employed to detect CO gas. Both sensors were used to evaluate relative changes in pollutant levels rather than absolute concentrations, while the system was controlled using an Arduino Uno. The scrubbing process was tested at two levels of water tap opening: full and half to observe the impact of water flow rate on pollutant removal.

3.2.1 CO and smoke reduction efficiency

CO and smoke reduction efficiency based on the test results: (1) at the full water tap position (Table 2): smoke reduction efficiency is 19.41% and CO gas reduction efficiency is 17.55%; (2) at the half-water tap position (Table 3): smoke reduction efficiency is 13.69% and CO gas reduction efficiency is 15.28%.

Reduction is more effective at the full water tap position due to the larger water volume and faster flow, resulting in a more efficient interaction between the pollutant and the water medium. This supports the fundamental principle of wet scrubber technology, which is to increase efficiency through the physical interaction between polluted air and the absorbing liquid [25].

3.2.2 Sensor data changes and stability

The input data graphs (Fig. 2, Fig. 3, Fig. 4, and Fig. 5) show significant fluctuations, caused by data collection in an open workshop area, which is exposed to various environmental factors such as wind speed, temperature, interference from other activities, and pollutant leaks from outside. This leads to instability in the sensor readings. The output data graphs in the figures show a more stable pattern because the data was collected in a room isolated with transparent plastic, minimizing external air contamination. This more secure environment results in more accurate sensor measurements of system performance. The difference in environmental conditions between input and output data collection significantly impacts sensor readings. This is an important factor when designing data collection methods to ensure more reliable results [26].

3.2.3 Assessment of safe air quality limits (SNI)

Referring to SNI standards: (1) SNI threshold parameters, measurement results in the workshop; (2) referring to Indonesian National Standards (SNI) for carbon monoxide exposure, the observed sensor readings indicate a potentially hazardous condition prior to scrubber operation. However, due to the use of non-calibrated gas sensors, the results are discussed in terms of relative reduction rather than absolute exceedance of regulatory limits [27].

Interpretation: the CO level assessment was compared qualitatively with SNI as a reference framework. Since the MQ-7 sensor does not provide calibrated concentration values in ppm or µg/m³, the comparison is used only to indicate potential exposure risk trends rather than regulatory compliance. Therefore, the results should not be interpreted as direct exceedance of SNI limits, but as relative indicators of improved air quality after scrubber operation. This condition has the potential to harm health, especially with prolonged exposure. CO can cause hypoxia, headaches, and even death. Metal fumes from welding activities can cause fever due to metal fumes, lung irritation, and other long-term impacts [28].

3.2.4 Implications and suggested solutions

The performance of the automatic wet scrubber system in this study is still low to medium, but it has shown the potential for significant pollutant reduction. Design improvements are needed, such as adding a water pressure pump to create a more stable flow. Improving the interaction area between water and air containing pollutants. Use bubble chambers or additional filters to increase effectiveness. The workshop environment requires serious attention. Natural and mechanical ventilation need to be improved. The use of exhaust ventilation systems and Personal Protective Equipment (PPE) should be prioritized. Training for workers and students on the risks of exposure to smoke and toxic gases should be provided.

This study has successfully demonstrated that automatic wet scrubbers are capable of removing CO and smoke from contaminated air, although their efficiency still needs to be improved. Environmental factors play a significant role in the stability of the measured data. With pollutant levels exceeding safe limits according to the SNI, implementing such a pollution control system is urgently needed to protect the health of the working environment in welding workshops [29].

4 Conclusions

A smoke removal device using an automatic wet scrubber method was successfully designed and built for a small to medium-scale welding workshop environment at the ATI Makassar Polytechnic. This system combines gas sensors (MQ-2 and MQ-7) that can automatically detect the presence of smoke and carbon monoxide gas, then activate the water pump and exhaust fan automatically via an Arduino microcontroller.

The observed differences in pollutant reduction efficiency between full and half water flow rates can be explained by the physical mechanisms of gas–liquid interaction in the wet scrubber system. Increasing the water flow rate enhances the formation of liquid droplets and increases the effective gas–liquid contact area, thereby improving the probability of smoke particles and gaseous pollutants being captured or absorbed. Higher water flow also promotes stronger turbulence inside the scrubber chamber, which increases pollutant residence time and collision frequency between the gas phase and liquid droplets.

In addition, the cylindrical drum filter design contributes to pollutant reduction by providing a confined space that guides the welding fumes through the spray region before exiting the system. This configuration increases the exposure of pollutants to the liquid phase; although the compact size of the drum limits the overall contact time compared to industrial-scale wet scrubbers. Consequently, while the system demonstrates measurable pollutant reduction, the relatively simple spray mechanism and limited chamber volume partially explain the moderate efficiency values obtained. These findings indicate that further performance improvements could be achieved through optimization of water flow rate, spray pattern, and chamber geometry.

Based on the research results, this wet scrubber is effective in absorbing smoke and filtering hazardous particles on average, with the water tap opening at full speed 19.41% smoke and 17.55% CO and with the water tap opening at half speed 13.69% smoke and 15.28% CO. Although the particle removal efficiency needs to be further tested quantitatively and qualitatively. The pollutant reduction efficiency obtained in this study (13–19%) is lower than that reported in several previous wet scrubber studies, which often achieved higher removal efficiencies under controlled laboratory or industrial-scale conditions. This difference can be attributed to several factors. First, the proposed system was designed as a compact wet scrubber for small-scale welding workshops, resulting in shorter gas–liquid contact time and lower spray pressure compared to industrial systems. Second, the experiments were conducted in open and closed workshop environments, where airflow disturbances and ambient ventilation may reduce pollutant capture efficiency. Third, the system operates with a simple water spray without chemical absorbents or high-pressure atomization, prioritizing low energy consumption and operational simplicity. In addition, pollutant reduction was evaluated using gas and smoke indicator sensors, which provide relative measurements rather than absolute concentrations. Therefore, the reported efficiency values should be interpreted as practical, sensor-based performance indicators rather than maximum achievable filtration efficiencies. Despite these limitations, the system demonstrates measurable pollutant reduction and highlights its potential for further optimization in real-world welding applications.

However, this study is limited by the laboratory-scale system design and the use of low-cost gas sensors, which may affect measurement accuracy and limit direct comparison with industrial-scale wet scrubber systems. Future work will focus on improving measurement accuracy and result comparability. This includes calibrating the MQ-2 and MQ-7 sensors using certified reference instruments, conducting experiments in a standardized and controlled test chamber to minimize environmental disturbances, and comparing the sensor-based results with measurements obtained from calibrated CO analyzers and particulate matter sensors (PM 2.5/PM 10). These steps are essential to enable quantitative performance evaluation and direct comparison with established air quality standards.

Acknowledgments

The author would like to thank his parents for their endless support, assistance, and prayers, and to Dr. Jufri, S.ST., M.T., and Enni Sulfiana, S.ST., M.T., for their valuable guidance, direction, and input. He would also like to thank his colleagues who helped in the design and data analysis process.

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