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Evaluation of Wet Scrubber Performance for Chlorine Gas Control in Glove Manufacturing: Operational Parameters, Emission Levels, and Safety Implications

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This study evaluates the performance and effectiveness of a wet scrubber system used for chlorine gas control in a glove manufacturing plant. The system utilizes a packed-bed wet scrubber integrated with a NaOH-based neutralization unit to capture chlorine-laden air from the chlorination room. The study employed on-site measurements of airflow, emission sampling, and chlorine leak simulations to evaluate the wet scrubber's operational performance under actual plant conditions. The scrubber treated air contaminated with chlorine gas (≤5 ppm), simulating release scenarios typical of glove manufacturing operations. The results showed that the face velocity measurements averaged 0.742 m/s, exceeding the recommended minimum of 0.50 m/s, affirming the system's capacity for effective contaminant capture. Ducting performance data, including velocity pressure, duct transport velocity, and volumetric flow rate, demonstrated consistent airflow and efficient pollutant transport within accepted industry ranges. Isokinetic emission analysis revealed that all monitored pollutants, including dust, chlorine, hydrogen chloride, ammonia, and non-methane volatile organic compounds, remain significantly below regulatory limits. Additionally, chlorine leak simulations highlighted the importance of sensor placement and ventilation in mitigating exposure risks, with recorded concentrations exceeding the time-weighted average (8-hr) limit of 0.5 ppm, underscoring the need for continuous monitoring and emergency preparedness. Overall, the wet scrubber system demonstrated high operational efficiency and regulatory compliance, contributing to a safer working environment and reduced environmental impact.

1. Introduction

The manufacturing of rubber gloves involves several key stages, and one of the important stages is the chlorination process. The primary purpose of chlorination is to enhance surface properties, making gloves safer, more comfortable, and easier to use (Preece et al., 2021). Chlorination chemically modifies rubber molecules by forming a chlorinated layer on the surface and reduces stickiness, facilitating easier handling and packaging. Furthermore, it improves grip and texture, making the gloves less slippery, which is crucial in healthcare and other delicate applications. The process also enhances glove durability by increasing strength, elasticity, and tear resistance, making them suitable for high-risk industries such as healthcare. Chlorinated gloves are also more resistant to degradation from chemical exposure, extending their usability in harsh environments (Luo et al., 2025).

Safety control measures for chlorine gas systems in rubber glove manufacturing facilities are critical to prevent leaks, ensure worker safety, and comply with industrial safety regulations. Wet scrubbers are vital engineering controls used to mitigate chlorine gas emissions in industrial settings (Rado-Foty et al., 2023). The wet scrubber is designed to treat contaminated air extracted from the chlorine room via a dedicated exhaust ducting system. When chlorine is released, ventilation airflow captures the gas and channels it through suction ducts to the wet scrubber, where it reacts with an alkaline scrubbing liquid, converting chlorine into non-toxic salts before the treated air is released (Tan, 2022). In addition to its technical design, the performance of a wet scrubber also depends on the pollutant load, in this case, the concentration of chlorine in the air entering the system (Gopa, 2025). These systems work by exposing chlorine-laden gas to a scrubbing liquid, typically an alkaline solution

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like sodium hydroxide ($NaOH$), which reacts with chlorine to form less harmful byproducts such as sodium hypochlorite ($NaOCl$) and sodium chloride ($NaCl$) (Flagiello et al., 2020). This neutralization process helps prevent environmental contamination and ensures compliance with occupational safety standards by effectively removing chlorine from the gas stream (Zhao et al., 2021). The main aim of this research is to evaluate the performance of a wet scrubber at a centralised chlorine gas manifold system in a rubber glove manufacturing plant. The analysis conducted was the face velocity analysis, ducting performance analysis (velocity pressure, duct transport velocity, and flow rate), isokinetic emission analysis, and chlorine leak simulation assessment.

2. Materials and Methods

2.1 Experimental Procedure

The study was conducted at a rubber glove manufacturing plant located at Bukit Beruntung, Selangor, Malaysia. The chlorination process in glove manufacturing involves treating latex gloves with chlorine gas to alter surface properties and reduce stickiness for improved usability. This performance test aimed to assess and validate the wet scrubber's ability to remove chlorine gas from the chlorination room during a simulated accidental release. Figure 1(a) shows the picture of the wet scrubber system and the chlorine gas control room (1b). The wet scrubber used in this study is a vertically oriented packed-bed scrubber fabricated from corrosion-resistant vinyl ester fiber-reinforced plastic (FRP), with a scrubbing column height of 5.5 m and a diameter of 1.6 m. The unit operates at a design airflow capacity of 3.5 m³/s and uses a 5% sodium hydroxide ($NaOH$) solution circulated at a rate of 200 L/min. Chlorine-laden air is introduced at the base of the column and rises counter-currently to the descending scrubbing liquid, promoting gas-liquid contact and absorption. The packing material consists of high-surface-area plastic media to enhance mass transfer efficiency. The performance efficiency test of the wet scrubber system was conducted using a standard chlorine canister containing 5.0 ppm chlorine gas. This test aimed to assess and validate the wet scrubber's effectiveness in removing chlorine gas from the chlorine room in the event of an accidental release. When the chlorine sensor detected a concentration of 2.0 ppm sustained for more than 10 seconds, the system automatically activated, triggering the emergency siren, starting the exhaust fan, and opening the suction duct damper controller. Chlorine gas was then captured and extracted by the wet scrubber system. The emission gas exiting through the wet scrubber's chimney (or stack), after passing through the air cleaning unit, was collected for further analysis to confirm the level of cleanliness. Chlorine gas continued to be released for 10 minutes or until the concentration dropped to 0.0 ppm, depending on real-time conditions. Throughout the test, the chlorine gas sensor continuously monitored the concentration levels within the chlorine room. The wet scrubber analysis was carried out using three important tools, such as TSI Digital Hot Wire Anemometer (to measure air flow, temperature and humidity), Pitot Tube (to measure static and velocity pressure), and Smoke Tube (to identify the direction of air flow).

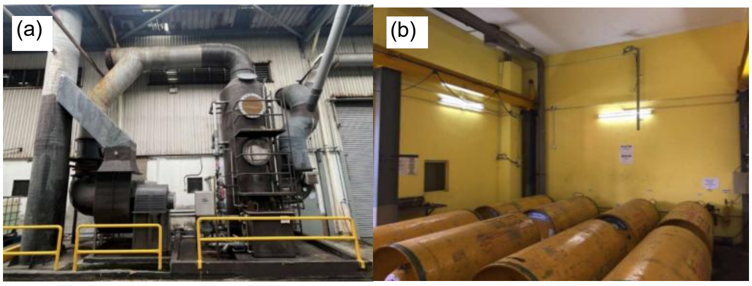

Figure 1: (a) Picture of wet scrubber system, (b) Chlorine gas control room

2.2 Face Velocity

The face velocity investigation was carried out using a thermal anemometer. The equipment was pre-calibrated to ensure the accuracy and reliability of measurements. A total of 100 sampling points were selected uniformly across the hood face area to represent the entire cross-sectional surface of the wet scrubber inlet. At each sampling point, the anemometer probe was positioned perpendicularly to the airflow and mounted on a fixed stand to minimize hand movement and maintain a consistent distance from the hood face. Each reading was taken after allowing the instrument to stabilize for five seconds, ensuring that the measurements reflected steady-state airflow conditions. Quality assurance was achieved by randomly selecting 10 out of the 100 total sampling points and performing duplicate measurements at those locations. This procedure helped assess repeatability and ensure consistency in airflow measurements across the hood face. This redundancy provided confidence in the data's consistency and helped detect any significant deviation.

2.3 Ducting Performance

The assessment was carried out for three key parameters: velocity pressure, duct transport velocity, and volumetric flow rate. The velocity pressure readings were taken at multiple points across the duct cross-section to ensure an accurate representation of airflow. Measurements were taken carefully to avoid errors caused by turbulence. Each reading was recorded in pascals (Pa), and multiple readings were taken at each point to improve data reliability and repeatability. The second parameter analysed was the duct transport velocity. Based on the collected velocity pressure data, the average air velocity moving through the duct was determined. The third parameter evaluated was the volumetric flow rate. This parameter was calculated by considering the cross-sectional area of the duct.

2.4 Isokinetic Emission Analysis

Five parameters were investigated for the isokinetic stack emission analysis, such as dust concentration, hydrogen chloride, chlorine, ammonia, and non-methane volatile organic compound (NMVOC). The equipment used for isokinetic emission sampling was the Microprocessor Based Advanced Stack Monitoring System (POLLTECH, Model PEM MK10M). The system measures directly the linear velocity of the gas stream in the stack, computes and continuously regulates the sampling flow rate to always meet true isokinetic sampling conditions during measurement. Sampling and velocity measurements were performed at a point of test at least eight stack or duct diameters downstream and two diameters upstream from any flow disturbance such as a bend, expansion or contraction in the stack.

2.5 Chlorine Leak Simulation Assessment

Chlorine leak simulation assessment is critical in assessing the safety and effectiveness of containment systems in glove manufacturing plants that handle chlorine gas. This assessment was carried out by first preparing the pre-testing, which included conducting a risk assessment to identify potential hazards related to the simulation. Proper personal protective equipment (PPE), such as self-contained breathing apparatus (SCBA) and protective clothing, besides the emergency water, was prepared before the assessment was carried out. The assessment was conducted using the same unit of chlorine gas room, which was used for the wet scrubber performance test.

2.6 Data Analysis

Analytical software packages, namely Excel and Minitab 19, were utilized for data processing and interpretation. Specifically, Minitab 19 facilitated the generation of control charts to continuously monitor chlorine concentration levels, allowing for timely detection of deviations from control limits. Regression analysis was conducted to examine the relationships among operational parameters and chlorine concentration outcomes, providing insights into potential factors influencing scrubber efficiency.

3. Results and Discussion

3.1 Face Velocity

For hazardous contaminants, such as chemicals or biological agents, maintaining an adequate face velocity is essential to prevent their dispersion into the workspace. The ACGIH (1998) guideline of 0.50 m/s represents a minimum threshold required to achieve effective removal containment. This standard is established to ensure that the airflow is sufficient to draw contaminants away from the breathing zone of personnel, reducing exposure risks. Table 1 shows that the average face velocity measurements were taken at various sampling points within the wet scrubber system in this study. The average face velocity recorded was 0.742 m/s, surpassing the ACGIH (1998) minimum requirement. This result is significant as it indicates that the system operates with a higher degree of airflow than the minimum necessary for effective containment. Such an outcome reflects the system's capability to efficiently manage hazardous substances, enhancing the safety of the working environment. Figure 2(a) illustrates the frequency distribution of face velocity measurements using a histogram with a normal distribution overlay. This helps visualize how closely the data aligns with a normal curve, suggesting uniform system performance. Figure 2(b) presents a probability plot, which assesses the data's statistical normality. A linear pattern in this plot confirms that the data are normally distributed, supported by a p-value < 0.005, indicating statistical significance. This reinforces the validity of the face velocity measurements and the effectiveness of the ventilation system. The higher average face velocity and statistically significant results affirm the system's efficiency and compliance with safety standards. This adherence is vital for maintaining a safe and healthy working environment, underscoring the importance of regular ventilation assessments in protecting both personnel and the environment from the risks of hazardous substances (NIOSH, 2015).

Table 1: Face velocity in wet scrubber

Variable	N	N*	Mean	SE Mean	StDev	Sum of Squares	Min	Q1	Median	Q3	Max
Face Velocity (m/s)	100	0	0.742	0.002	0.023	55.128	0.700	0.722	0.740	0.760	0.790

Note: N = Number of observations, N* = Number of missing observations, SE Mean = Standard Error of the Mean, StDev = Standard Deviation, Q1 = First Quartile (25th percentile), Q3 = Third Quartile (75th percentile), Min = Minimum value, Max = Maximum value.

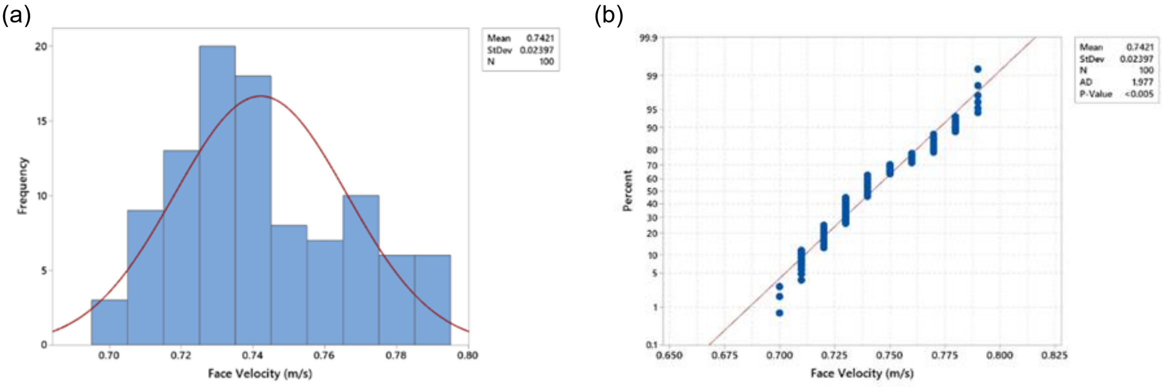

Figure 2: (a) Histogram (with normal curve) of face velocity (m/s) for wet scrubber, (b) Probability plot of face velocity (m/s)

3.2 Ducting Performance

This section presents a comprehensive assessment based on the analysis of three primary parameters: velocity pressure, duct transport velocity, and volumetric flow rate. Velocity pressure reflects the kinetic energy of air flowing through the duct and is directly related to the duct's airflow velocity. The data for velocity pressure, as shown in Table 2, reveal an average of 28.531 Pa, with a standard deviation of 2.556 Pa, suggesting moderate variability. The minimum (Min) value recorded was 24.653 Pa, while the maximum was 33.570 Pa, indicating a controlled and consistent duct airflow with acceptable pressure fluctuation across the sample size (N = 100). These results suggest that the duct system maintains stable energy transfer, necessary for overcoming friction and maintaining airflow through bends and fittings within the duct network.

Table 2: Ducting performance of wet scrubber

Variable	N	N*	Mean	SE Mean	StDev	Min	Q1	Median	Q3	Max
Velocity Pressure (pa)	100	0	28.531	0.256	2.556	24.653	25.860	28.566	31.082	33.570
Duct Transport Velocity (m/s)	100	0	6.8889	0.0309	0.3087	6.4100	6.5650	6.9000	7.1975	7.4800
Flow Rate (m^3/s)	100	0	3.0449	0.0136	0.1364	2.8332	2.9017	3.0498	3.1813	3.3062

Q1 = First Quartile (25th percentile), Q3 = Third Quartile (75th percentile)

Duct transport velocity is crucial for ensuring that contaminants are carried effectively through the ducting system without settling or re-entrainment. According to the ACGIH (1998) guideline, a minimum air velocity in the range of 5 to 10 m/s is recommended for typical contaminant transport. The recorded mean duct transport velocity of 6.889 m/s falls well within this optimal range, confirming that the system is operating within acceptable limits for effective contaminant conveyance (Table 2). The volumetric flow rate, which is the total volume of air moved per unit time, provides a measure of the wet scrubber's overall capacity to handle contaminated air. The analysis shows a mean flow rate of 3.045 m^3/s, with a relatively low standard deviation of 0.1364 m^3/s, signifying operational stability (Table 2).

3.3 Isokinetic Emission

The isokinetic emission results are presented in Table 3. The results are compared against Malaysian Environmental Quality (Clean Air) Regulations 2014 and various US EPA methods for different pollutants. The dust concentration was recorded at 0.76 mg/Nm^3, which is significantly lower than the permissible limit of 50 mg/Nm^3. This indicates that the wet scrubber effectively removes particulate matter, ensuring minimal environmental impact. Hydrogen chloride (HCl) emissions were non-detectable (ND), with levels below 0.0001 mg/Nm³, compared to the regulatory threshold of 30 mg/Nm³, demonstrating the system's excellent acid gas neutralization capabilities. For chlorine gas (Cl_2), the recorded concentration was 0.33 mg/Nm³, which is well below the allowable limit of 5 mg/Nm³, signifying the wet scrubber's efficiency in controlling chlorine emissions, a critical factor for compliance and safety. Similarly, ammonia (NH_3) emissions were also non-detectable (ND) at levels below 0.0001 mg/Nm³, far below the limit of 30 mg/Nm³. Additionally, non-methane volatile organic compounds (NMVOC) were non-detectable (ND) at levels below 0.0001 mg/Nm³, well under the regulatory limit of 150 mg/Nm³. This further attests to the system's effectiveness in preventing VOC emissions. All emission parameters are well within the permissible limits outlined by the Environmental Quality (Clean Air) Regulations 2014. This reflects the robust design and maintenance of the wet scrubber system, ensuring compliance with environmental standards and reducing potential harm to the surrounding environment.

Table 3: Analysis of isokinetic emission

Parameter	Result (mg/Nm^3)	Environmental Quality (Clean Air) Regulations 2014 (mg/Nm^3)
Dust Concentration	0.76	[1]50
Hydrogen Chloride, HCL	ND < 0.0001	[2]30
Chlorine gas, Cl_2	0.33	[3]5
Ammonia, NH_3	ND < 0.0001	[2]30
NMVOC (non-Halogenated)	ND < 0.0001	[4]150

Note: [1]means Second Schedule, (I), No.2; [2]means Fifth Schedule, Category (4)(a), Class (3); [3]means Fifth Schedule, Category (4)(a), Class (2); [4]means Second Schedule, Regulations 13, (II)

3.4 Chlorine Leak Simulation

Figure 3 illustrates the chlorine profile during the leak simulation test using two sensors. For Sensor 1, Test 1 shows a mean chlorine concentration of 1.096 ppm, with a standard deviation of 1.037 ppm. The minimum value observed is 0.000 ppm, indicating the absence of chlorine in some measurements, while the maximum value reaches 3.400 ppm. In Sensor 1, Test 2, the mean concentration rises to 1.486 ppm with a higher standard deviation of 1.195 ppm. For Sensor 2, Test 1 reports a mean concentration of 1.357 ppm and a standard deviation of 1.141 ppm. Like Sensor 1, the minimum value is 0.000 ppm, but the maximum value is slightly lower at 3.600 ppm. In Sensor 2, Test 2, the mean concentration increases to 1.726 ppm with a standard deviation of 1.514 ppm. This test shows the highest maximum value of 4.400 ppm. The provided data highlights variability in chlorine concentration, which is significant when considering health and safety. Prolonged or high-level exposure can lead to more severe health problems, such as chronic respiratory conditions or damage to the mucous membranes. According to the U.S. Environmental Protection Agency (EPA), the Permissible Exposure Limit (PEL) for chlorine gas is 0.5 ppm based on an 8-hour time-weighted average (TWA).

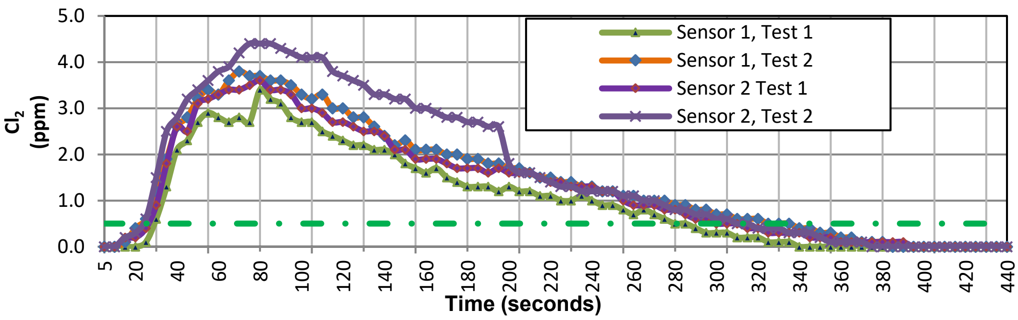

Figure 3: Chlorine profile during leak simulation test

Figure 4(a) shows the 95% confidence intervals for the mean chlorine (Cl_2) concentrations measured by each sensor during two separate tests. The wider intervals in Sensor 2 Test 2 reflect higher variability and a greater likelihood of exceeding exposure thresholds. These confidence bounds help quantify the uncertainty in the measurements and reinforce the need for robust mitigation strategies in high-risk zones. Figure 4(b) is a dot plot where each grey dot corresponds to an individual chlorine concentration measurement recorded during the simulation. The x-axis categorizes the tests (Sensor 1 Test 1 and Sensor 1 Test 2). The spread of points along the y-axis illustrates variability. Blue dots denote the mean values per group, and wider spreads indicate greater variability in exposure at that sensor and test condition. Sensor 1, Test 1 displayed a wide spread of data, with values ranging from 0 to nearly 3.5 ppm, and a dense cluster around 1 ppm. Sensor 1, Test 2 showed a broader range of concentrations and a slightly higher mean value. Sensor 2, Test 1 revealed a more tightly packed data cluster, indicating stable chlorine levels and lower variability. In contrast, Sensor 2, Test 2 had the widest range of values, with concentrations reaching up to 4 ppm, reflecting the highest levels of chlorine exposure detected during the simulation.

(a) (b)

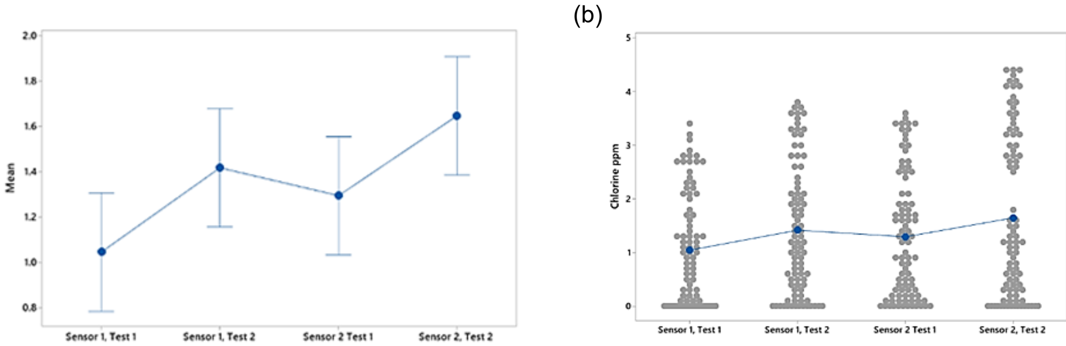

Figure 4: (a) Interval plot of 95 % confidence level for the mean chlorine concentration during leak simulation, b) Individual plot of chlorine concentration during leak simulation for each sensor and test

4. Conclusions

The evaluation of the existing wet scrubber system demonstrated that the system was generally well-maintained and operationally effective in minimizing chlorine gas exposure. From a performance standpoint, the system's average face velocity of 0.742 m/s exceeded the recommended minimum of 0.5 m/s, indicating sufficient airflow to capture and contain airborne contaminants effectively. The velocity pressure, duct transport velocity (mean: 6.889 m/s), and volumetric flow rate (mean: 3.045 m^3/s) all fell within acceptable ranges for efficient contaminant transport. These parameters exhibited low variability and normal distribution patterns, reflecting stable system dynamics and the ability to maintain effective ventilation under operational conditions. The isokinetic emission analysis confirmed the wet scrubber's high pollutant removal efficiency. All tested emissions, including chlorine gas (0.33 mg/Nm^3), dust (0.76 mg/Nm^3), and various volatile compounds (HCl, NH_3, NMVOC), were significantly below the permissible limits. These findings affirm the scrubber's effectiveness in mitigating environmental discharge and maintaining regulatory compliance.

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