PM 2.5 REDUCTION BY THE SMART ABSORPTION TOWER-CONTROLLED SYSTEM USING IOT

AKASIT WANSOM

A Thesis Submitted to the Graduate School of Naresuan University
in Partial Fulfillment of the Requirements
for the Doctor of Philosophy in Smart City Management and Digital Innovation
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has been approved by the Graduate School as partial fulfillment of the requirements for the Doctor of Philosophy in Smart City Management and Digital Innovation of Naresuan University

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Academic Paper Ph.D. Dissertation in Smart City Management and Digital Innovation, Naresuan University, 2023

Keywords

ABSTRACT

This research was done to be as a model and project guideline. One form of using technology is to solve the problem of PM2.5 in cities. Fine Particulate Matter like PM 2.5 affects people in the town a lot during the dry season in North Thailand and Bangkok. One of the leading causes of PM2.5 generation is traffic problems, which seriously impact pedestrians on roadsides and at public bus stops. Therefore, this research has two phases. Phase 1 The research was studied, designed, and produced air purification towers by studying the experiment's four techniques such as 1) Droplet sizes, 2) Turbulence water, 3) Packed-beds material, and 4) Surfactants, until it led to a hybrid water purification tower system. This PM2.5 air purification tower was obtained by studying various variables until a water spray system combined with a turbulence water system was used to remove PM2.5. It was more efficient than 80% at droplet size 270 microns with a liquid-to-air ratio of 9 in the spray section and water level 100-150mm above the nozzle in the turbulence water part. According to conditions tested in the laboratory using Internet of Thing technology to help measure results in real-time and find efficiency. After that, try using the clean air values from the hybrid wet scrubber to design the air duct system with the computation Fluid Dynamics (CFD) simulation software to measure the results if the clean air tower was installed with the airflow outlet duct system at the bus shelter.

Finally, in phase 2, the PM2.5 air purification tower was installed at the bus shelter on the road in front of the hospital in Phitsanulok City during the dry season from March to April for 60 days. The bus shelter also was modified to be a semi-enclosed area. The result shows that the PM2.5 air purification tower has purification efficiency similar to the results in the laboratory. The cleanliness value of the air exhaust pipe meets the standards of both WHO and the Pollution Control Department of Thailand. However, the clean air volume of five to six cubic meters per minute from the air purification tower could dilute the air in the bus stop by 25-50% because it depends on the air diffusion with the wind speed that enters from the passing car.

ACKNOWLEDGEMENTS

This dissertation was completed with kindness and support from Professor Dr. Tharapong Vitidsant, the Head of the Center of Fuels and Energy at Biomass, Chulalongkorn University. He always gave suggestions and support during the study and experiments in the lab for this research. I want to thank my advisor in smart city management and digital innovation in the Ph.D. program, Associate Professor Dr. Pisit Maneechot, and my co-advisor, Associate Professor Dr. Prapita Thanarak, during the study and the research at The School of Renewable Energy and Smart Grid Technology, Naresuan University, Phitsanulok, Thailand. I want to thank the research budget from the Broadcasting and Telecommunications Research and Development Fund for Public Interest, which has made it possible to bring knowledge and studies into actual experiments in the laboratory and the field. I want to thank the Phitsanulok Municipality for providing the station at the bus shelter for the experiment. I thank Associate Professor Dr. Tawat Suriwong for commenting on developing the content and format for writing this project proposal and research. Thank you, Dr.Pornnipa Nunocha, for your help and advice in organizing this research book.

Finally, I would like to thank my wife and family for understanding that I have to take valuable family time, which is already limited due to work, and put it into study and research. I hope this research will help readers develop ways to use scientific knowledge to solve air quality problems in cities and improve people's living standards.

Akasit Wansom

TABLE OF CONTENTS

Page

List of tables

Page

List of figures

Page

CHAPTER I

INTRODUCTION

1.1 The Global and Thailand PM 2.5 Problem Situations

PM 2.5, "Particulate Matter 2.5", was the fifth cause of death worldwide in 2015, and 7 million people died worldwide from air pollution in 2016. People died because of outdoor air pollution, which reached 4.2 million people, and 91 percent lived in Asian countries and the West Pacific. In Thailand, air pollution contributes to more than 50,000 premature deaths per year [1]. PM 2.5 is a significant problem for people, especially those living in Thailand and Bangkok's northern provinces. The PM 2.5 concentration is much higher than the standard of the WHO and the Department of Pollution Control of Thailand from November to April every year. This problem affects public health and the economy. The Thai government has asked for cooperation from the government, the private, and the public in issuing several measures and procedures to mitigate the impact on health, the environment, and the economy [1-5]. In Bangkok, PM 2.5 originates from vehicle emissions from transportation and biomass combustion. In the dry season between January and April every year, 45% of the PM 2.5 pollution in Bangkok comes from diesel-powered vehicles [6], with the highest value of PM 2.5 not exceeding 300 $\mu m/m^3$.

1.2 The Effects of PM 2.5 and the Solutions for Thailand's Smart Citys

Bangkok, Thailand's capital city, also faces this problem, especially in early 2019 and 2020. According to the Institute for Management Development (IMD), Bangkok is 71st in the Smart City Index 2020 because residents in Bangkok have consistently identified air pollution and road congestion as significant problems [7]. The major cities in northern Thailand, such as Chiang Mai and Phitsanulok, experienced the same issues and increased violence annually. The PM 2.5 problem has affected the well-being of urban people in terms of health, economy, and the environment.

Thailand's smart city has seven domains: smart energy, smart mobility, smart living, the smart economy, smart people, smart governance, and the smart environment. A smart environment is deemed codependent on all other domains, so it is required for inclusion in any project enrolled in the Smart City Thailand program [8]. Cities must address PM 2.5 air quality problems to improve and increase living standards in a clean-air environment. One dimension of the project is essential for being a smart city under the Thailand 4.0 project, as a smart environment is considered a compulsory urban development into a smart city. In this study, a PM 2.5 smart control device was designed and built to reduce the impact of PM2.5 in semienclosed areas and crowded spots in urban areas. This device could be installed at semi-enclosed parking garages, bus shelters, or bus stations along the roadside in Phitsanulok city. The PM 2.5 problem has affected the well-being of urban people in terms of the health economy.

Many end-of-pipe technologies, such as cyclones, scrubbers, electrostatic precipitators, and baghouse filters, are available to eliminate and reduce the levels of PM 2.5 in air pollutants. The effectiveness of each of these techniques depends on how the device is designed and applied. For instance, a cyclone can filter dirty air with 90% efficiency and can filter dust with a diameter greater than 20 µm. The removal efficiency of a spray tower can reach 90% for particles with a diameter exceeding 5 µm, and it typically falls within the range of 60% to 80% for particles with diameters ranging from 3 µm to 5 µm. When particles have a diameter of less than 3 µm, the removal efficiency of a spray tower decreases to less than 50%. The venturi scrubber boasts a removal efficiency of 98% and can effectively filter particles as small as 0.5 µm in diameter. The electrostatic precipitator has a dirty-air-filtering efficiency of 99%. It can filter dust 1 µm in diameter but consumes substantial power. The baghouse's dirty-air-filtering efficiency is nearly 100%. It can filter dust that is 1 µm in diameter; however, this device has high levels of airflow resistance and is expensive to operate and maintain [9, 10].

Kim et al. [11] conducted a theoretical analysis of the removal efficiency of a gravitational wet scrubber particle that considered impaction, interception, and diffusion. Impaction generally removes dust particles with a diameter greater than 1 µm; the Brownian diffusion mechanism can remove particles smaller than 0.1 µm in diameter. Jiuan [12] also maintained that a countercurrent flow arrangement is more efficient than a crossflow arrangement. Thus, particles are conditioned during scrubbing by wetting, trapping in water blankets, and impacting them with water droplets. Numerous factors influencing the scrubbing process must be considered to enhance the efficiency of wet scrubbers, including scrubber design, sizing, droplet size, packed bed material, packed bed depth, selection of scrubbing liquid, and distribution rate of the washing liquid [13]. In this study, we examined the improvement in the removal efficiency of a counterflow spray wet scrubber and its PM 2.5 removal efficiency by reviewing and experimenting with four techniques. Four variables are relevant to PM removal efficiency enhancement: (1) droplet size (for a wet spray scrubber), (2) packed bed, (3) turbulence water, and (4) surfactants in the wet scrubber. Smaller droplets can capture finer particles because they have a larger surface area-to-volume ratio. However, if the droplet size is too small, the momentum of the pollutant airflow can be imparted to the droplets. Decreasing the relative velocity between the droplet and particles results in a decrease collection efficiency [9]. The purpose of a packed bed is to increase the area of contact between two or three phases in a scrubbing process, such as liquid and gas in a scrubbing process [14]. The height and type of packing can be changed to improve the mass transfer. A larger packed bed depth is preferred for a scrubber since it helps boost absorption and efficiency [15]. Many packing types, such as the Pall ring, Raschig ring, Tri-packs, Tellerette, Berl saddle, Intalox, and others, are made from various materials [16]. The U.S. EPA suggests that packed-bed scrubbers are more suitable for gas scrubbing than for PM scrubbing, as clogs in the bed and plugging make it more difficult to access, clean, and change the spray heads. A packed-bed wet scrubber can be used for low dust-loading applications for particulate matter larger than 5 µm. A deflector and baffle create water turbulence, allowing polluted air to flow through fluctuating water. This method can simultaneously increase the wettability of particles, cause agglomerate, and remove dust [17]. Meikap et al. [18] achieved a removal efficiency ranging from 95% to 99% for particulate matter particles with sizes ranging from 0.1–100 µm in a modified multistage bubble column scrubber. Lee et al. [19] reported that a swirling cyclone wet scrubber could collect 2.5 µm particles with an efficiency of 86% and 5 µm particles with an efficiency of 97%. Park et al. [20] observed that wet scrubbing with polydisperse aerosols can remove more than 90% of particles larger than 2 µm. Mohan [21] reported 75–99%

PM2.5 removal efficiency with a novel spray-bubbler scrubber in which the bubble column removed the most particles when the concentration increased. Park [20] investigated the performance of a water turbulence scrubber for the removal of particulate matter and found that particles larger than 1 μm were drawn efficiently (nearly 100%), depending on the flow rate, dust-laden air stream concentration, and the reservoir water level. Hence, spray columns and bubble column scrubbers are efficient at scrubbing particulate matter from effluent [17]. The objectives of this research were to determine the effect of each parameter and their combination on the PM 2.5 removal efficiency, to design an actual size wet scrubber in a bus shelter for the protection of pedestrians from roadside traffic pollution, and to monitor the real-time PM 2.5 concentration with an IoT system to calculate the accurate removal quantity of PM 2.5.

1.3 Research Problems

Roadside bus terminals are where people in a city are affected by air pollution. How could we reduce the effects of air pollution at bus shelters?

1. Air purifiers generally work effectively in enclosed spaces. How could we use air purifiers in public areas?
2. How could we produce clean air that meets the PM 2.5 standards prescribed by the WHO or Thai Air Quality Standards?

1.4 Research Questions

1. Will this device reduce PM2.5 at the installation point, and how effective is it?
2. What technology or techniques were used to construct this device?

1.5 Research Objectives

1. A smart adsorption tower-controlled system using IOTs at bus terminals could reduce the amount of polluted air and provide clean air for people to breathe according to the WHO's PM 2.5 standard or Thai air quality standards.
2. The use of purification tower techniques to improve the efficiency of the wet scrubber tower was studied.
3. IoT sensors and data management on a cloud platform were developed to measure the performance of a PM 2.5 absorption tower in real time under various parameters or technical adjustments to study the efficiency of the air purification tower.

1.6 Research Scopes

1. A 3-phase air purification tower was designed and constructed.
2. Study four techniques, the droplet size of spray water, packed beds, surfactants, and water turbulence, were used to increase the performance of the conventional wet scrubber.
3. The IoT system, sensors, and cloud-based application were integrated into the air purification tower to study the performance.
4. The smart air purification tower was built and installed in the laboratory and bus shelter target areas in the Phitsanulok Municipality.
5. The data are collected and analyzed, the problem is visualized, and the impact of the problem is weighed.

CHAPTER II

THEORIES AND LITERATURE REVIEW

2.1 What is PM 2.5?

PM 2.5 is defined as airborne particulate matter with a diameter of less than 2.5 microns and is among the eight prevalent air pollutants; these include carbon monoxide (CO), lead (Pb), ground-level ozone (O_3), nitrogen dioxide (NO_2), ammonia (NH3), sulfur dioxide (SO2), and particulate matter (PM)10 and 2.5 and are collectively recognized as criteria air pollutants [4].

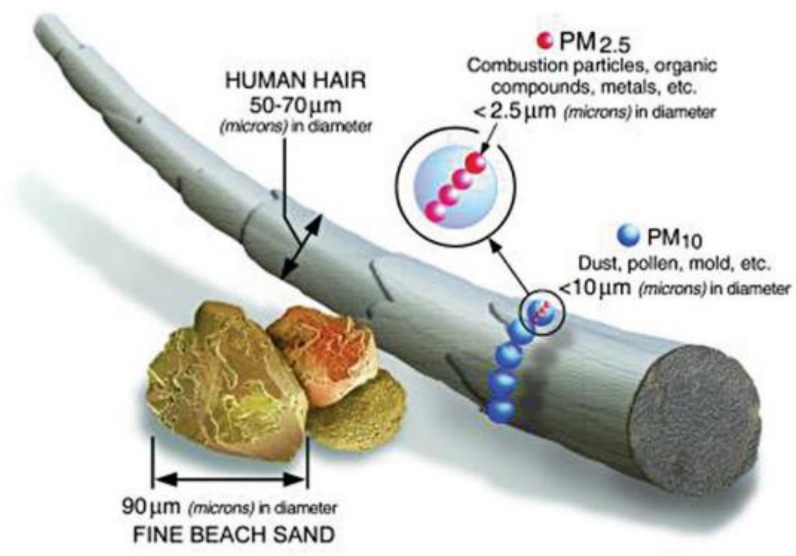


Figure 1 Size of PM 2.5 [4]

2.2 Emission Sources.

Fine dust originates from automobile fumes, power plants, industrial plants, construction, and agricultural incineration and includes smoke from cooking food made from firewood, as shown in Figure 2. In addition, sulfur dioxide (SO_2) oxides of nitrogen (NOX) and volatile organic compounds (VOCs) react with other substances in the air to form fine dust [4].

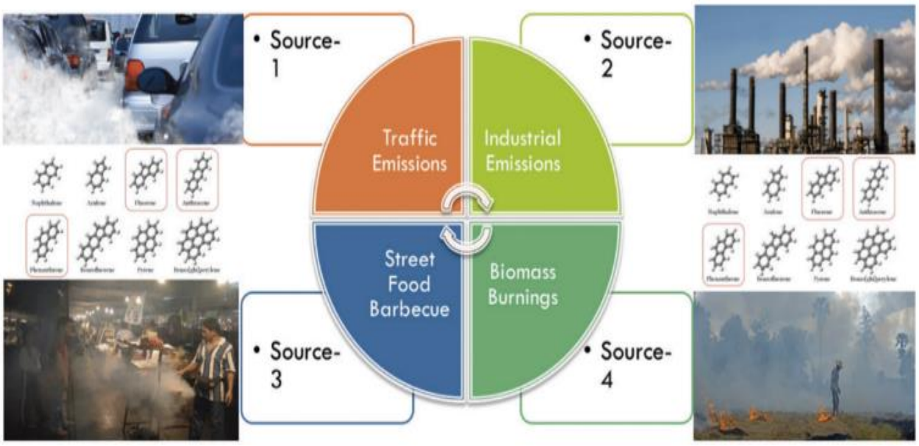


Figure 2 Emission sources [4]

2.3 The Effects of PM 2.5.

The PM 2.5 problem has affected the well-being of urban people in terms of health, economy, and the environment.

2.3.1 Impact on People's Health.

PM 2.5 has been shown to disrupt human well-being, particularly by impacting the health of various groups such as children, older adults, and individuals with respiratory conditions. PM 2.5 not only poses an immediate threat to health but can also cause a range of health disorders. Regrettably, the adverse effects of air pollution caused by minute particulate matter (PM 2.5) on air quality and its association with various health issues, including respiratory illnesses, cardiovascular health, and allergic symptoms affecting the eyes and nasal passages, have sparked worries [1, 2, 4].

PM 2.5 was found to interfere with human life as it affects the health of many people, especially the effects on children, elderly individuals, and patients with respiratory diseases. Unfortunately, air pollution with tiny particulate matter (PM 2.5) has raised concerns about the negative impact of air quality on several health conditions, including respiratory illness, heart health, and allergic symptoms affecting the eyes and nasal passages. The primary concern about these tiny particles is their ability to travel through the respiratory tract and deep into the lungs. PM 2.5 may not cause immediate harm to health; cumulative exposure over time can lead to various health disorders. One of the dangers related to PM 2.5 may be its ability to carry other harmful environmental pollutants into the body through the adhesive properties of its outer layer, e.g., carcinogens and heavy metals [4]. The particle size of PM 2.5 can cause many diseases, such as heart disease, atherosclerosis, chronic respiratory disease, cancer, and diabetes. Various studies have shown that the air is infected with many different microbes, bacteria, fungi, and viruses. These microorganisms can bind to air pollutants and enter the human body, impacting health. Older adults are more at risk than middle-aged people because the incidence of emphysema and other cystic fibrosis increases with age, and respiratory function deterioration with age can have a more significant impact. Moreover, children and infants are more at risk than adults because the lungs are developing [1, 4]

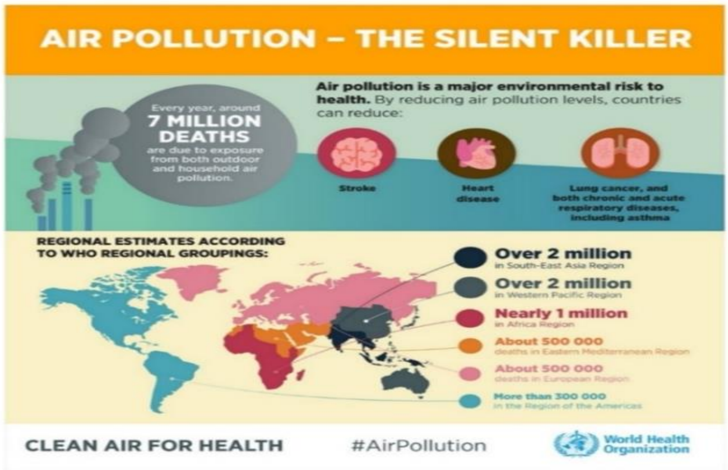


Figure 3 Global deaths from air pollution (Source: WHO)

Figure 3 shows that PM 2.5, "Particulate Matter 2.5", was the fifth cause of death worldwide in 2015, and 7 million people died worldwide from air pollution in 2016.

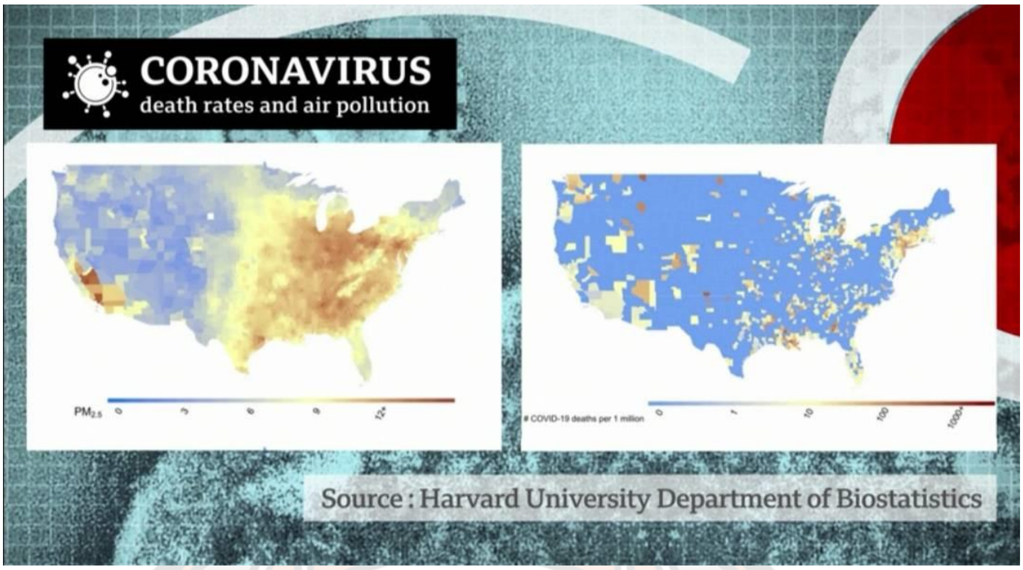


Figure 4 Coronavirus incidence, death rate, and air pollution status (source: Department of Biostatistics Harvard University)

Recent Harvard research has also shown that an increase in PM 2.5 will result in an approximately 15% increase in COVID-19 mortality, as shown in Figure 4 [22].

2.3.2 Impact on the Thai Economy

PM 2.5 and PM 10 also affect the economy from individual and household to national levels. Both schools and educational institutions have announced the cessation of teaching. People must buy masks and air purifiers. A greater number of visits to the doctor for patients with respiratory problems affects the tourists. For example, Kasikorn Research Center (2020) estimated that PM 2.5 affects the economy by 3,200-6,000 million baht in the month, divided into the cost of health opportunities 2,000-3,000 million baht, such as medical expenses, mask costs, and air purifiers, tourism opportunity costs 1,000-2,400 million baht and other business opportunities such as street food, food garden, and the market 200-600 million baht [23].

A study examining the influence of PM10 on the Thai economy revealed the following findings. In 2019, an economic damage cost of THB 18,420 million was identified for each microgram per cubic meter (µg/m3) of PM10 exceeding the safe standard. It was determined that a household was willing to contribute 6,379.67 THB annually to reduce one microgram per cubic meter (μg/m3) of PM10 in Bangkok. When this value was multiplied by the 2017 household count of 2,887,274 in Bangkok (according to the Department of Provincial Administration, 2018), the result was an economic damage cost of 18,420 million THB for each 1 μg/m3 of PM10 exceeding the established safe standard [24]. Assuming an even distribution of the impact across every Thai household, Thailand would have incurred 1.79 trillion THB in societal damage from PM10 pollution in 2017. This accounted for 11.62% of the country's GDP for that year. Adjusting the assumption of the impact distribution of PM10, with 75% of the Thai households affected, the damage figure would have been THB 1.35 trillion (8.71% of GDP); at 50%, it would have been THB 0.90 trillion (5.81% of GDP). Since there is currently no quantitative study on the economic damage caused by PM 2.5 in a similar fashion, the utilization of the quantitative impact of PM10 may serve as the minimum estimated damage [24]. The societal adverse effects of PM 2.5 are likely to be more pronounced than those of PM10 because of its comparatively more hazardous nature.

The problem of air pollution is a growing concern for the public in Thailand. The Royal Government of Thailand has issued an official statement regarding air quality, which is on the national agenda of PM 2.5. It was established in February 2019 by the Thai government, and private and academic agencies have joined to fix and determine PM 2.5.

2.4 Thai Air Quality Index

The air quality index conveys information about air pollution, and various countries employ air quality indices. Thailand's air quality standard assesses and juxtaposes the levels of five prevalent air pollutants with established standards in the ambient atmosphere. These assessed air pollutants include ozone gas (O3), nitrogen dioxide gas (NO2), carbon monoxide gas (CO), sulfur dioxide gas (SO2), particulate matter with a diameter of 10 microns or less (dust PM10), and particulate matter with a diameter of 2.5 microns or less (PM 2.5) [4]. Thailand's air quality standards at the national level are less stringent than the recommendations put forth by the World Health Organization. The yearly average for the most hazardous pollutant, PM2.5, is

15 µg/m3, three times greater than the WHO guideline. Similarly, the daily standard is established at 37.5 µg/m3, which is 2.5 times higher than the corresponding WHO recommendation [1, 5].

Table 1 PM 2.5 Air Quality Index, Thailand, vs. the WHO

		PM 2.5 micrograms per cubic meter
THAILAND	Annual mean	15
	24-hour mean	37.5
WHO	Annual mean	5
	24-hour mean	15

The Thai people can monitor real-time air pollution levels and air quality indices, which are readily available online via mobile device applications such as RGuard, Air4thai.com, IQAir AirVisual, and Windy.com or via websites such as www.aqmthai.com, http://air4thai.pcd.go.th/webV2/, and https://pm2_5.nrct.go.th.

2.5 Guideline to solve PM 2.5 air pollution problem

Currently, we are considering the guidelines to solve this problem in 3 areas.

1. At emission sources that have produced PM 2.5, such as industrial factories, vehicles, and burning in the agricultural sector, we must strictly enforce the law to reduce pollutants at sources such as factories.

2. Atmosphere: PM diffuses in the air, and we have no technology available to prevent it. PM can travel everywhere by distribution because it is difficult to control the movement of the air.

3. At the receptors, inhalation affects people directly. Today, we reduce the effect on people by wearing masks outside and using portable air purifiers in homes, offices, or cars to relieve some of the impact on people.

Using end-of-pipe technology, which comprises air pollution control devices aimed at removing dust from air pollutants, encompasses techniques such as cyclones, scrubbers, electrostatic precipitators, and baghouse filters. Nevertheless, the efficiency of each approach relies on its specific design and intended applications [9, 10].

2.6 Air pollution control technics

There are four conventional methods for managing fine particulates through physical processes and equipment: cyclones, scrubbers, electrostatic precipitators, and baghouse filters. Each type of air-control device is unique and has advantages and disadvantages. Hence, engineers need to tailor the design of devices and control systems to specific cases. Critical factors related to particulate characteristics, such as corrosiveness, reactivity, shape, density, dust size, and size distribution, play key roles in determining suitable collection devices. Additionally, design considerations encompass airstream characteristics (pressure, temperature, and viscosity), the air change rate, the flow rate, removal efficiency requirements, and permissible resistance to airflow.

2.6.1 Cyclones

Cyclone collectors are usually used to remove coarse particulates from the air. A cyclone removes particulates, causing the dirty airstream to flow in a spiral path inside a cylindrical chamber. Polluted air enters the room from a tangential direction at the outer wall of the device, forming a vortex as it swirls within the section. Because of their greater inertia, the larger particulates move outward and are forced against the chamber wall. Slowed by friction with the wall surface, they slide down the wall into a conical dust hopper at the bottom of the cyclone. The cleaned air swirls upward in a narrower spiral through an inner cylinder and emerges from an outlet at the top. The accumulated particulate dust is periodically removed from the hopper for disposal. Cyclones are best at removing relatively coarse particulates.

2.6.2 Electrostatic precipitators

Within an electrostatic precipitator, particles in the airstream undergo electric charging upon entering the unit, and the influence of an electric field facilitates their removal. The precipitator unit includes features like baffles for airflow distribution, discharge electrodes, collection electrodes, a dust clean-out system, and collection hoppers. A high DC voltage (up to 100 kilovolts) is applied to the discharge electrodes to charge the particles. An electrostatic precipitator can effectively exceed 99 percent eliminate particulates as small as one µm. The frequent use of electrostatic precipitators in power stations is attributed to their efficacy in removing fly ash from the combustion gases of fossil fuel furnaces.

2.6.3 Baghouse filters

A standard baghouse consists of a series of elongated, slender bags, each approximately 25 cm (10 inches) in diameter, suspended in a spacious enclosure with the open ends facing downward. Fans blow dust-laden air upward through the lower section. The filter bags capture the particulates, allowing the purified air to pass through the fabric and exit from the top of the baghouse. A fabric-filter dust collector can eliminate nearly 100 % of particles as small as 1 mm in length and a notable proportion as small as 0.01 mm in length. Nevertheless, fabric filters present a comparatively elevated resistance to airflow and entail substantial operational and maintenance costs. Furthermore, to extend the lifespan of the filter fabric, the purified air must cool, typically below 300°C, before passing through the unit. A baghouse filter necessitates the use of cooling coils, which can increase expenses, especially when individual containers require cleaning while others remain in active service.

2.6.4 Wet Scrubbers Devices

Wet scrubbers trap suspended particles by direct contact with water or other liquid sprays. A tiny liquid droplet scrubs the particulates out of the dirty airstream. Several wet scrubbers are spray-tower scrubbers, and an upward-flowing airstream is washed by water sprayed downward from a series of nozzles. The scrubber efficiency depends on the relative velocity between the droplets and the particulates.

These systems exhibit reduced water-recirculation rates and provide removal efficiencies of approximately 90% for particles larger than two μm. The counterflow spray wet scrubber demonstrated greater efficiency than the crossflow spray wet scrubber. Among wet collectors, Venturi scrubbers are the most effective, achieving efficiencies exceeding 98% for particles larger than 0.5 μm in diameter. The efficiency of scrubbers hinges on the relative velocity between the droplets and the particulates [9, 10]. Hence, the scrubbing process conditions particles through wetting, capturing them in water blankets and impacting them with water droplets.

Table 2 Summary of air pollution control techniques

C	Detail	Efficiency	Disadvantage
Cyclones	A cyclone removes particulates by causing the dirty airstream to flow in a high-velocity spiral path inside a cylindrical chamber.	Its efficiency in filtering dirty air is 90%. It can filter dust at a 20 μm level.	Its efficiency is lower than other techniques. It is used as a precleaner.
Wet scrubbers	Wet scrubbers eliminate dust particles by entrapping them in liquid droplets, which are subsequently gathered. The liquid then dissolves or absorbs the pollutant gases.	Its efficiency in filtering dirty air is 90%. It can filter dust larger than 8 μm level. The venture scrubber efficiency is 98% and can filter to 0.5 μm.	Its filter efficiency is lower than other techniques.

Table 2 (Cont.)

C	Detail	Efficiency	Disadvantage
Electrostatic precipitators	An electrostatic precipitator (ESP) removes the fine particles of the flowing gas, like smoke and dust. It uses direct current (DC) with a high voltage of over 100,000 volts.	Its efficiency in filtering dirty air is 99%. It can filter dust at one µm level.	Use more electric power to filter dirty air.
Baghouse	The baghouse eliminates dust particles as a fan propels dust-laden air upward through the enclosure's bottom. Initially, particulates are captured within the filter bags, after which the purified air traverses through the fabric and exits from the top of the baghouse.	Its efficiency in filtering dirty air is nearly 100%. In addition, it can filter dust at one µm level.	High airflow resistance. It is expensive to operate and maintain.

Byeong-Kyu Lee (2013) demonstrated the efficiency of each technique in removing tiny particles, as shown in Figure 5:

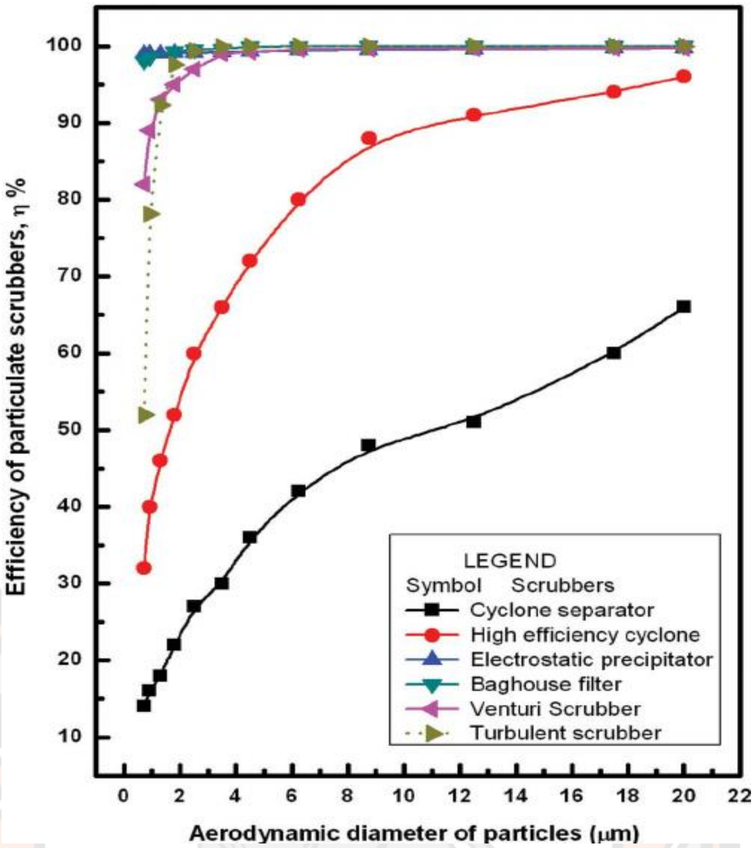


Figure 5 Comparison of the efficiencies of various particle removal techniques [17]

From the four technology standards, we can also add additional technical knowledge from mechanical or chemical methods to increase performance.

2.7 Countercurrent flow wet scrubber technology

According to this research, the wet scrubber technology has been chosen for dust collection. The study provides additional details on this technology through its design and studies of techniques to add to the tower to increase the performance of this device. Wet scrubbers have collection efficiencies ranging from 50% to 90% , depending on the design and application. Several techniques can improve the efficiency of wet scrubbers, such as a) water spray wet scrubbers, which can remove particles larger than eight µm in diameter. b) A wet scrubber with a packed bed can remove particles larger than 2 µm, and c) A venturi scrubber can support removing particles larger than 0.5 µm. (11) As a wet scrubber uses liquid to remove pollutants, called the scrubbing process, two fundamental removal mechanisms are associated with particle removal from the process stream in the scrubber, namely impaction and Brownian diffusion. Impaction generally removes more than one μm of dust, and the Brownian diffusion mechanism can remove particles less than 0.1 μm in diameter. We also found that the counterflow arrangement is more efficient than the crossflow arrangement [12]. There are still many factors to be considered when improving the efficiency of the scrubber, such as the scrubber design, size, packed-bed material, packed-bed depth, selection of scrubbing liquid, and washing liquid distribution rate, which affect the scrubbing process. The Environment Protection Agency (EPA) has also suggested wet scrubbers, such as those with a diameter of a droplet at 500 μm and a liquid-to-gas ratio of 2.71 l/m^3 for the tiny particulate matter used to eliminate PM 2.5 in cement plants [13].

2.7.1 Design of the counterflow wet scrubber

Principles of airflow

The air movement between two locations occurs from the pressure disparity between them. The air volume, often denoted in cubic feet per minute (CFM), is symbolized by Q. The speed of the air, measured in feet per minute (ft/min), is denoted by V. The dimension of the conduit or ductwork pertains to the area specified in square feet (ft^2), represented by the symbol A.

The equation expresses the airflow through a conduit (ductwork) or a filter:

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

Air change rate

The prevalent expression for denoting the quantity of outdoor air required in a building is air changes per hour (ACH). The ACH can fluctuate significantly based on the activities occurring within the building. For instance, a minimum air change rate of 4 ACHs is commonly acknowledged for commercial or industrial structures. The following is a good reference table for more common building use and the ACH.

Table 3 Air change rate per hour for each area [25]

Building/Room	Air Change Rate in ACH
All Areas in General	4
Auditorium	8 – 15
Bakeries	20 – 30
Beauty Shops	6 – 10
Boiler Rooms	15 – 20
Classrooms	6 – 20
Computer Rooms	15 – 20
Dental Centers	8 – 12
Garages –Repair	20 – 30
Hospital Rooms	4 – 6
Kitchens	15 – 60
Machine Shops	6 – 12
Malls	6 – 10
Municipal buildings	4 – 10
Police Stations	4 – 10
Precision Manufacturing	10 – 50
Shops, Paint	15 – 20
Wood Shops	5
Theatres	8 – 15
Warehouses	6 – 30
Waiting Rooms, Public	4

From "The Engineering Toolbox" website at **www.engineeringtoolbox.com [25]**

Due to the lack of theory for designing an absorber tower to eliminate PM 2.5, the design of the tower relies on the design of the dissolved gas evaporator as a guideline [12] :

The size of the absorption tower was calculated.

We chose one cubic meter of airflow to be cleaned in one minute to constitute the protocol for design.

Therefore, we consider airflow = 60 m^3/hr. =35.31 Cfm = 16.67 l/s.

Liquid and gas ratio

From $G_m(Y_0 - Y_1) = L_m(X_1 - X_0)$

$G_m/L_m = 1$

Tower diameter

The essential value for design is as follows:

$$abscissa = \left(\frac{L_{mol,i}}{G_{mol,i}}\right)\left(\frac{MW_L}{MW_G}\right)\sqrt{\left(\frac{\rho_G}{\rho_L}\right)} \quad (2)$$

$L_{mol,i} = G_{mol,i}$ MW_G = 29 g, MW_L =18 g ρ_G = 1.2754 kg/m^3 ρ_L = 1000 kg/m^3

$abscissa = 1x0.621x0.036 = 0.022$

From Eckert's modification to the generalized correlation, ordinate = 0.1

$$Ordinate = \frac{(G_{sfr,i})^2 \psi F_{P\left(\frac{\mu_L}{2.42}\right)^{0.2}}}{\rho_L \rho_G g_c} \quad (3)$$

$$G_{sfr,i} = \left[\frac{\rho_L \rho_G g_c (ordinate)}{F_P \psi \left(\frac{\mu_L}{2.42}\right)^{0.2}}\right]^{0.5} \quad (4)$$

The ratio of liquid that eliminates gas density to water density is Ψ = 1, Gravity g_c = 32.2ft/s^2, water density ρ_L = 62.42 lbs/ft^3 air density ρ_G= 0.079 lbs/ft^3, packing facter F_P = 1 and water viscosity μ_L= 2.153 lbs/ft-hr

$G_{sfr,i} = 4.03$

$$A = \frac{G_{mol,i} MW_G}{3{,}600 G_{sfr,i}\, f}$$

$G_{mol.i}$= 72,000 g/hr 29g = 2,482 mol/hr Air molecular weight MW_G = 29 g flooding factor f = 0.75

A = L^2 for a square surface

Select L = 0.8 m.

Therefore, the surface area of the 0.8x 0.8 =0.64 m^2 tower is greater than the calculated data.

Tower height

$$N_{TU} = \frac{ln\left[\left(\frac{y_1 - mx_1}{y_0 - mx_0}\right)\left(1-\frac{1}{AF}\right)+\frac{1}{AF}\right]}{1-\frac{1}{AF}} \quad (5)$$

Absorption factor $AF = \frac{L_{mol,i}}{mG_{mol,i}}$ m approach 0 A.F. approach ∞

So $N_{TU} = \ln\frac{y_1}{y_0}$

$N_{TU} = 5.298$

According to the data, the height of the T.U. tower is approximately 0.39 m.

H = N_{TU} x T.U.

H = 2.06 m for areas exposed to water and air

Ensuring that the ductwork system supplies the appropriate air volume to and from each room and maintaining year-round comfort is crucial. This involves conducting heat loss and heat gain calculations for each room. The equal friction method is usually used to design air pipes, and the Dercy-Weisbach equation is used to design water pipes. However, if our system is small and the pipe system is concise, we can provide pipes according to the air pump and water pump size because there is little loss from the pipe system [13, 25-28].

2.8 Liquid-to-air ratio and droplet size to increase the PM2.5 removal efficiency

Smaller droplets possess a better excellent surface area-to-volume ratio, enabling them to capture finer particles effectively. Nonetheless, when the droplet size becomes excessively small, the momentum of the pollutant airflow may transfer to the droplets, diminishing the relative velocity between the droplet and the particles. The efficient removal of PM 2.5 is achieved through the use of tiny water droplets and slow-moving air, thereby increasing the liquid-to-air ratio [18].

2.9 Turbulence water increases the PM 2.5 removal efficiency

Introducing a deflector and baffle induces turbulence in the water, allowing the contaminated air to pass through fluctuating water. This approach can enhance the wettability of particles, promote their agglomeration, and facilitate dust removal simultaneously [17]. Using a modified multistage bubble column scrubber, Meikap et al. (2004) attained a removal efficiency of 95-99% for particulate matter spanning sizes ranging from 0.1 μm to 100 μm [18]. Park and Lee (2008) discovered that a cyclone wet scrubber with swirling motion can achieve an efficiency of 86% for collecting particles of 2.5 μm and an efficiency of 97% for particles of 5 μm [19]. Park and Lee (2009) reported that aerosols polydispersed by wet scrubbing can remove more than 90% of particles larger than 2 μm [20]. Raj Mohan et al. (2009) reported that particulate removal of approximately 75–99% of particulates was achieved by using a novel spray-cum-bubbler scrubber. The result showed that the bubble column removed most particles when the concentration increased [21]. Byeong-Kyu Lee (2013), examining the effectiveness of a water turbulence scrubber for eliminating particulate matter removal, researchers have observed highly efficient capture of particles larger than one μm, reaching nearly 100%. The efficiency depended on the flow rate, dust-laden air stream concentration, and reservoir water level. Consequently, spray columns and bubble column scrubbers are more convenient for removing particulate matter from effluent [17].

2.10 Packed-bed technique to increase the PM 2.5 removal efficiency

The packed bed aims to enhance the contact area between two or three phases during a scrubbing process involving substances such as liquids and gases [14, 15]. Adjustments can be made to the height and type of packing to enhance mass transfer. A greater packing depth is desirable in scrubbers because it promotes absorption and efficiency. Various forms of packing, including Pall rings, Raschig rings, Tri-packs, Tellerette, Berl saddles, Intalox, and others, are crafted from diverse materials [29]. According to the US EPA (1998), packed-bed scrubbers are recommended for gas scrubbing rather than for PM scrubbing because dealing with bed clogs and plugging is more challenging when accessing, cleaning, and replacing spray heads. Moreover, packed-bed wet scrubbers are applicable for low dust-loading scenarios and for capturing particulate matter larger than 5 μm [30].

A packed bed is a hollow tube, pipe, or other vessel filled with packing material. The packing can be filled with small objects such as Raschig rings, zeolite pellets, granular activated carbon, or a specifically designed structured packing.

The purpose of a packed bed is to improve contact between two phases in a process, such as through the use of liquids and gases. Packed beds can be used in a chemical reactor, a distillation process, or a scrubber process [14, 15, 30].

Liquid and vapor distributions (vapor to liquid ratio)

In addition to the packing shape and surface area, another performance factor is the vapor-to-liquid ratio that enters the packed bed. In increasing the efficiency of the mass transfer. The design of the liquid distributors used to introduce feed and reflux to a packed bed is critical for ensuring that the packing can perform at maximum efficiency [14-16].

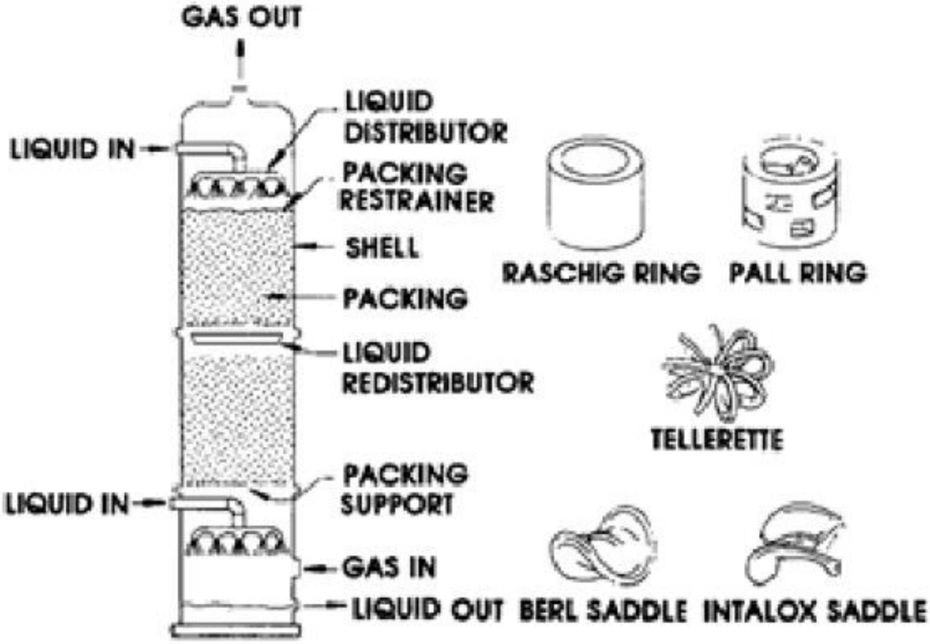


Figure 6 Packed bed scrubbers with some packing types retrieved [29]

The depth of packing influences the absorption performance. A greater packing depth is favored in a scrubber because it contributes to absorption, thereby improving its efficiency.

For the design, the cross-sectional area of the tower (ft^2) is calculated as

$$A = \frac{G_{mol,i} MW_G}{3{,}600 G_{sfr,i}\, f} \tag{6}$$

where f is the flooding factor, and 3,600 is the conversion factor from hours to seconds. To prevent flooding, the column is operated at a fraction of $G_{sfr,i}$ The value of f typically ranges from 0.60 to 0.75, using. $G_{sfr,i}$ from the formula

$$G_{sfr,i} = \frac{\rho_L \rho_G g_c (ordinate)}{F_P \psi (\frac{\mu_L}{2.42})^{0.2}} \tag{7}$$

where F_P Is the packing factor for which F_P depends on the type of packed bed and the manufacturer.

2.11 Surfactant technique for increasing PM 2.5 removal efficiency

The air-water interface, which has robust cohesive forces between water molecules and high surface tension, is considered. As surfactants absorb, these interactions are disrupted (32). These molecules possess both hydrophobic and hydrophilic components, making them amphiphilic and able to be absorbed in the air-water interface. The hydrophobic material is in the air, and the hydrophilic material is in water, as shown in Figure 7.

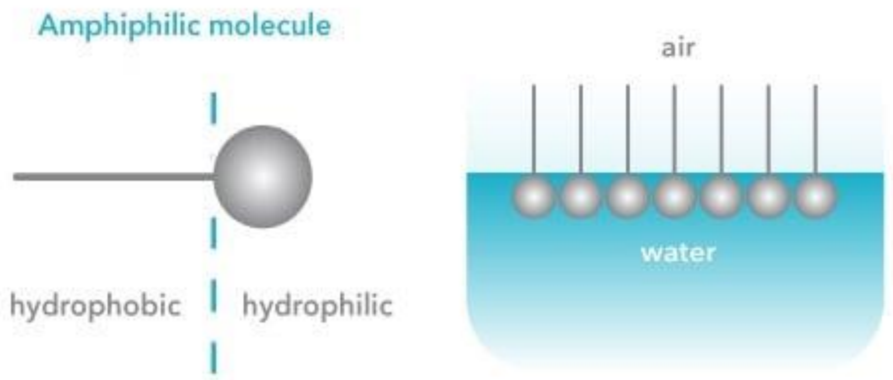


Figure 7 Surfactant's structure [31].

Surfactant basics

Surfactants are amphiphilic molecules with hydrophobic and hydrophilic parts absorbed at the air water interface. The hydrophobic component is in the air, and the hydrophilic component is in water. The hydrophobic tail is a hydrocarbon, fluorocarbon, or siloxane. They will cause a decrease in surface or interfacial tension and stabilize the interface [32].

Surfactants are commonly categorized according to their polar head, with the hydrophobic tails often exhibiting similarity. When the head group lacks a charge, the surfactant is termed nonionic. The material is referred to as anionic or cationic in the presence of a negative or positive charge on the head group. If the surfactant incorporates positive or negative groups, it is labeled zwitterionic.

In the industry, the most widely employed types of surfactants are anionic and nonionic. Notably, anionic surfactants are utilized in cleaning products such as laundry detergents and shampoos. Conversely, nonionic surfactants are commonly employed as wetting agents in the food industry. Cationic and zwitterionic surfactants, on the other hand, have more specific applications, mainly due to their higher production costs.

Table 4 Four Surfactant Types

Surfactant type	Example	Use
Anionic	Alkyl sulfates, soaps, Calsoft®, Texapon®	50 % of overall industrial production, laundry detergent, dishwashing liquids, shampoos
Cationic	Quaternary ammonium salts	Used together with nonionic surfactants but not with anionic, softeners in textiles, anti-static additives
Nonionic	Ethoxylated aliphatic alcohol, polyoxyethylene surfactants, Triton™ X-100, Span®, Tergitol™	45 % of overall industrial production, a wetting agent in coatings, food ingredient
Zwitterionic	Betaines, amphoacetates	Expensive, special use e.g. cosmetics

The focus was solely on the air water interface. The cohesive forces among water molecules are strong, resulting in a high surface tension. Upon absorption, surfactants disrupt these interactions, and the intermolecular forces between surfactants and water molecules are considerably weaker than those between two water molecules, thereby reducing surface tension. With a high concentration of surfactant, micelles are formed. The concentration at which micelles are formed is called the critical micelle concentration.

Surfactants are typically classified based on their polar head. If the head group has no charge, the surfactant is called nonionic. Anionic surfactants are a class of surfactants that can generate hydrophobic anions after ionization in water, while cationic surfactants have the opposite effect. Zwitterionic surfactants are cationic surfactants when the pH of the solution is less than 7. When the pH of the solution is greater than 7, the solution is an anionic surfactant. Surfactant agents reduce the surface tension of water, improve their ability to wet surfaces and form fine droplets. Reduced surface tension and random collisions between droplets of water and fine dust particles result in the wetting and enlargement of the dust particles such that they drop out of suspension in the air [33-39]. Dust suppression Surfactant-enhanced spraying dust capture can be divided into four steps: collision, contact, aggregation, and sinking [34], as shown in Figure 8.

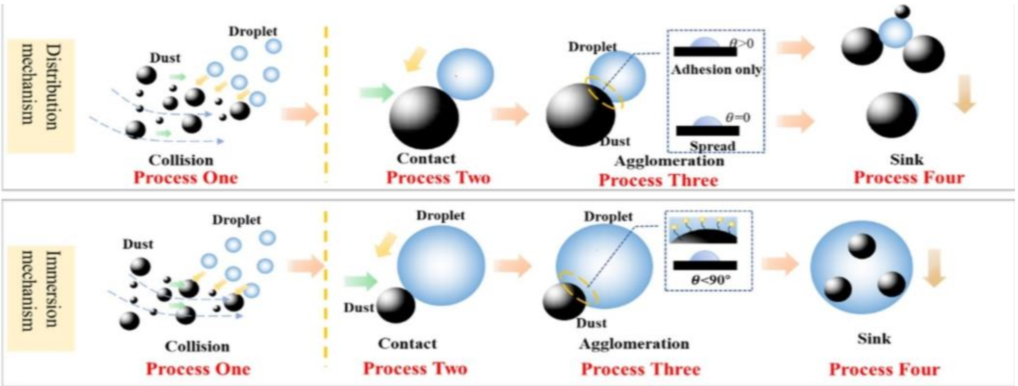


Figure 8 Collision between droplets and particles, contact between particles and droplets, agglomeration of wetted particles, and sinking of aggregates [34]

Upon reaching its critical micelle concentration (CMC), the surfactant solution experiences saturation during the adsorption of surfactant molecules on the liquid surface. When the concentration of the surfactant solution surpasses its CMC, stable micelles composed of several to hundreds of ions or molecules form in the solution as the concentration continues to increase. However, the characteristics of the air-liquid interface remain unaffected. Hence, the CMC serves as a pivotal point: before this threshold, increasing the concentration alters the properties of the air-liquid interface, while after the CMC, the solution forms micelles, and the interface properties remain unaltered [34].

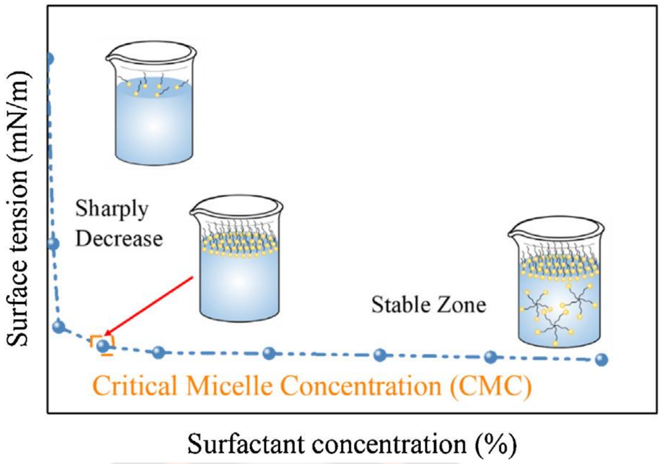


Figure 9 Critical micelle concentration [34]

There was no substantial decrease in the surface tension of the solution as the concentration increased. The concentration was called the critical micelle concentration (CMC) under these conditions. The influence of surfactant type and mass concentration on wetting ability was closely linked, as indicated by the contact angles of the four surfactant solutions at various mass concentrations. With an increase in solution concentration, the contact angle of the droplets on the compact coal dust consistently decreased. According to the Young equation, the contact angle of the liquid on the solid surface correlates with the interfacial tension. Notably, the results of the surface tension experiment indicated that two surfactant types, namely SDBS and OP-10, outperformed the others in reducing surface tension. SDBS and OP-10 reached the critical micelle concentration (CMC) of 0.005%. Adding an additive further decreased the surface tension of the surfactant solution, albeit the change was marginal. In the coal dust wetting experiment, as the surfactant concentration increased, the contact angle of the droplets on the coal dust tablets consistently decreased, signifying a continuous increase in the wetting ability of the surfactant solution, as shown in Figure 10. (36)

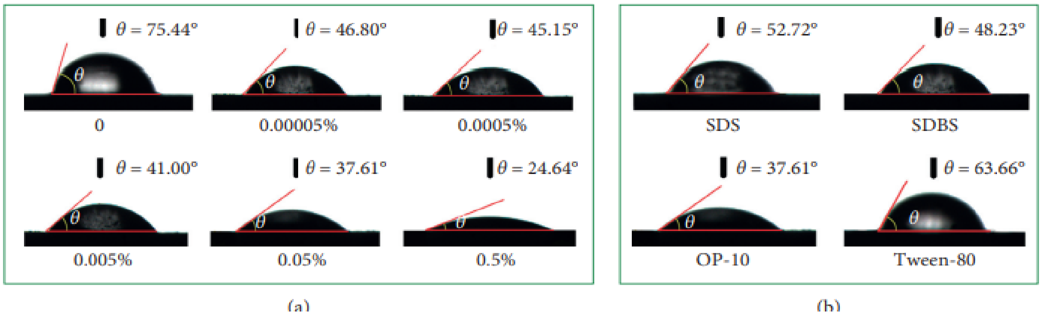


Figure 10 Contact angle projections of four surfactant solutions: (a) increase in surfactant concentration and (b) type of surfactant. [36]

2.12 Internet of Things and Data Communication Technology

2.12.1 Internet of Things (IoT)

The Internet of Things (IoT) refers to devices, objects, and other manufactured or artificial living facilities with embedded electronic circuits, software, sensors, and network connections. These objects can be stored and exchanged for their data. The data can also control the environment remotely through a smart device connection infrastructure. Smart devices such as smartphones or tablets and the IoT can be used to be interconnected on the Internet to communicate. According to the IEEE P2413 standard, we can divide the components of the IoT into three layers as follows:

(1) The application layer is a layer of data processing and storage. This layer includes the device and server for user interfaces, such as websites or mobile applications for displaying or controlling devices.

(2) The network layer is a connection layer through a network system. Most often, the IoT is used for wireless networking. This layer connects and sends data between the devices and servers, such as data read from sensors from the device layer forwarded to the application layer or data processed and shipped to control devices at the device layer.

(3) The sensing layer is a layer of devices that can be connected via methods such as control boards, sensors, or actuators.

2.12.2 Edge Computing

Edge computing processes data as close to the source as possible, possibly through data analysis or statistical data processing. Instead of requiring vast amounts of data to be processed in the Cloud, these data are processed those data at the source closest to the edge. Edge computing technology features must be considered when designing an IoT system, such as 1) Geographic dispersion of devices, 2) internet connectivity, and 3) data privacy/security.

2.12.3 Sensor Technology

A sensor refers to devices, circuits, or systems that measure changes in properties or the nature of things around the target object and bring vast amounts of data. When the sensor measures the value, it will be a signal from the system, which will change proportionally according to the measured values. In general, sensor devices can be divided into three types according to their measurement properties:

(1) A physical sensor is a sensor used to measure physical properties, such as a sensor used to capture images, temperature, and humidity.

(2) A chemical sensor is a sensor used to measure various chemicals. For example, a specific chemical reaction can be converted into data or signals that can be read and analyzed, such as through the use of sensors for measuring environmental contaminants such as soil and water.

(3) Biosensors are sensors that use biological recognition materials to react with specific target substances, such as sensors used to measure blood sugar levels.

Sensor features

The Selection of a sensor for a system depends on several factors, such as cost, utility, and environmental components. Understanding sensor characteristics is essential. A suitable detector needs to be selected. The features of the sensor are

1. The accuracy is expressed as a percentage of the full-scale value. For example, a thermometer may guarantee an accuracy of 5%.

2. The sensitivity is the relationship between the input signal and the output.

3. The linearity of the sensor on a graph shows the relationship between output and input that is close to a straight line. Sensor applications are typically used only in the linear range.

4. Range: The sensor's operating range is defined as the limit at which the sensor can function effectively.

5. The sensor's resolution relates to the slightest input or the minor change it can detect. The higher the display resolution is, the smaller the ability to measure or perceive the image.

6. The sensor's response is when it takes to provide the final output value for the given input. It may be expressed in terms of seconds. For example, in the specification, the sensor takes 3 seconds to output 95% of the full-scale value.

7. Frequency response: The input to the sensor may be constant. The number of cycles of fluctuation in a unit of time is called the frequency. Sensors with high natural frequencies can be applied to static and dynamic loads.

8. The dead zone refers to the most significant change in the measured quantity without changing the output or the input range without production in the dead area because of static friction or hysteresis.

9. The ability to repeat (reliability or reproducibility) or precision is the number of times the original measurement is obtained. Repeatability may be supplied as ± the maximum percentage of readings or under the limiting conditions of each task.

10. Stability measures the sensor's input change under constant input conditions for an extended period.

11. The reliability is the sensor's ability to work under specified conditions. The set period or the number of times the specified operation occurred while subject to sensor specifications. The sensor reliability is similar to the sensor lifetime.

12. Operating life The benefit of a sensor's lifespan indicates how long the sensor is expected to operate within a given specification. The lifetime is expressed in terms of the time, number of uses, or cycles the sensor should withstand.

13. Dual sensitivity sensors are typically designed to measure only one quantity, such as pressure or force. However, sensors may also be sensitive to other factors, such as temperature; if a sensor measures particular quantities in a process where temperature changes, such as pressure, errors can occur due to dual-sensitivity sensors measuring two portions simultaneously.

14. Many digital sensors in large numbers have replaced analog signal sensors because of the use of all types of processors. In addition, sensors with digital transmissions provide more accurate information.

2.12.4 Wireless Communication Technology Wireless Technology

The diversity of wireless communication technologies that support IoT operations today can be divided into two main groups: first, short-range communications will connect devices not exceeding 1,000 meters, and second, long-distance communication groups will connect devices with more than 1000 meters of communication distance. There are two subgroups of long-distance communication: licensed frequency segments, such as NB-IoT, and unlicensed spectra, such as LoRa. Usage in each group depends on the application and the needs of that network. Many wireless technologies can be selected for use in the system, such as

(1) Near-field Communication (NFC) PAS ISO 14443 at a frequency of 13.56 MHz. Examples of popular applications include tracking goods, accessing out of the buildings, etc. Another key technology is radio frequency identification (RFID), which identifies product information using a radio frequency in logistics and RFID instead of barcodes (barcode).

(2) Wireless Personal Area Network (WPAN) The leading technologies in this group are Bluetooth and ZigBee. Bluetooth is a technology that is

very popular for short-distance communication, such as communication between smartphones and external devices.

(3) The wireless local area network (WLAN), or Wi-Fi, is a top-rated wireless communication network. Today, IEEE 802.11 a/b/g/n is widely used at 2.4 GHz. Additionally, additional standards, such as IEEE 802.11ac at 2.4 and 5 GHz, are being developed to meet the demands of new applications.

(4) The wireless wide area network (WAN) WWAN group refers to the former cellular communication group, and a new group called the low power wide area (LPWA) supports low-speed communications. It has a long battery life. Additionally, devices can be connected over a long distance. Here, they can be divided into two subgroups:

- Licensed Spectrum or Cellular

The broadband communications used include GSM, WCDMA, LTE, and 5G, commonly known as the 3rd Generation Partnership Project (3GPP) technology. NB-IoT (narrowband Internet of Things) technology, which is designed to transmit data up to 100 kbps over a narrow range of 200 kHz bandwidths, has been used to support low-speed communication. The battery life ranges from 6 months to 10 years, depending on usage and device features. This approach is suitable for integration with both mobile and stationary sensors.

- Unlicensed Spectrum

LoRa and SIGFOX were developed to support work on applications and machine-to-machine communication to maintain low-power communication and long communication distances.

2.12.5 Wireless communication protocol between server and client

(1) Communication via the MQTT Protocol

Message Queue Telemetry Transport (MQTT) is an open protocol with limited code size and bandwidth that provides communication between the client and server as a publish/subscribe transport protocol. The MQTT protocol can transmit any format data type desired by the user, such as ASCII, JSON, or binary data. The MQTT protocol relies on a non-binding method. The publish/subscribe messaging protocol is divided into the publishing party and the subscriber receiving the information. The MQTT protocol consists of a broker, publisher, and subscriber, each of which has the following functions:

1. The broker acts as an intermediary to manage messages based on the topic. There are many MQTT broker programs available. One is Mosquito MQTT, the most popular of which is used today in IoT development.

2. The subscriber will watch for changes to the message referring to the topic and, for example, assume that the data will be used if the subject of interest is changed.

3. The publisher will serve to send information on that topic.

The function of MQTT is to send data between the server (broker) and clients (publisher/subscriber) by publishing the traffic topic called the topic in the broker. Then, the publisher sends the information to that topic, and the subscriber obtains all the information.

(2) Communication via the HTTP protocol with the REST API

The HTTP (hypertext transfer protocol) is a standard communication method between web servers and clients on web browsers that uses a request-and-response communication method. IoT devices communicate via the HTTP protocol, often via the communication method of the REST API.

REST, or representational state transfer, creates a web service that relies on HTTP methods (GET, POST, PUT, and DELETE) and returns a result in JSON or XML. REST popularity is an issue associated with using traffic because it produces value in JSON or XML formats, which are small and easily extracted [39-54]

CHAPTER III

RESEARCH METHODOLOGY

3.1 Design and Construction of the Absorption Tower

Due to the lack of theory for designing an absorber tower to eliminate PM 2.5, the design of the absorption tower relies on the design of the dissolved gas evaporator as a guideline [12]:

The size of the absorption tower was calculated. We designed an absorption tower based on an actual wet scrubber in a bus shelter (10 m*2 m*3 m) to protect pedestrians from roadside traffic pollution and monitor the real-time PM2.5 concentration with an IoT system to calculate the accurate removal quantity of PM 2.5. Then, one cubic meter of airflow was cleaned in one minute to constitute the protocol for the design.

Therefore, we consider airflows of 1 m^3/min or 60 m^3/hr. =35.31 Cfm =16.67 l/sec.

Liquid and gas ratio

From $G_m(Y_0 - Y_1) = L_m(X_1 - X_0)$

$G_m/L_m = 1$

Tower diameter

The essential value for design is as follows:

$$abscissa = \left(\frac{L_{mol,i}}{G_{mol,i}}\right)\left(\frac{MW_L}{MW_G}\right)\sqrt{\left(\frac{\rho_G}{\rho_L}\right)} \quad (8)$$

$L_{mol,i} = G_{mol,i}$ MW_G =29 g MW_L =18 g ρ_G =1.2754 kg/m^3 ρ_L =1000 kg/m^3

$$abscissa = 1x0.621x0.036 = 0.022$$

From Eckert's modification to the generalized correlation, ordinate = 0.1

$$Ordinate = \frac{(G_{sfr,i})^2 \psi F_{P(\frac{\mu_L}{2.42})^{0.2}}}{\rho_L \rho_G g_c} \quad (9)$$

$$G_{sfr,i} = \left[\frac{\rho_L \rho_G g_c(ordinate)}{F_P \psi\left(\frac{\mu_L}{2.42}\right)^{0.2}}\right]^{0.5} \tag{10}$$

The ratio of liquid that eliminates gas density to water density is Ψ =1, gravity g_c=32.2 ft/s^2, water density ρ_L=62.42 lbs/ft^3, air density ρ_G = 0.079 lbs/ft^3, packing facter FP =1 and water viscosity μ_L=2.153 lbs/ft-hr

$$G_{sfr,i} = 4.03$$

$$A = \frac{G_{mol,i} MW_G}{3{,}600 G_{sfr,i}\, f}$$

$G_{mol.i}$=72,000 g/hr 29 /g =2,482 mol/hr. Air molecular weight MW_G =29 g flooding factor f = 0.75

A = L^2 for a square surface

Select L = 0.85 m.

Therefore, the surface area of the 0.85x0.85 tower is 0.72 m^2 greater than the calculated data.

Tower height

$$N_{TU} = \frac{ln\left[\left(\frac{y_1 - mx_1}{y_0 - mx_0}\right)\left(1 - \frac{1}{AF}\right) + \frac{1}{AF}\right]}{1 - \frac{1}{AF}} \tag{11}$$

Absorption factor $AF = \frac{L_{mol'i}}{mG_{mol,i}}$ m approach 0 A.F. approach ꝏ

So $N_{TU} = \ln \frac{y_1}{y_0}$

$N_{TU} = 5.29$

According to the data, the height of the tower transfer unit is approximately 0.39 m.

H = N_{TU}x Transfer Unit

H = 2 m for areas exposed to water and air

The duct of airflow using the equal friction method [25]

We consider flow = 60 m^3/hr

The air velocity was set to 1,300 fpm as recommended.

Duct diameter = $\sqrt{(0.027 * 4/\pi)}$ = 0.185 ft = 2.22”

From the equivalent of a circular duct, circular to rectangular was converted, then a rectangular size = $6'' * 6''$ was selected, and the duct design friction chart was used to determine the friction loss 0.1 inches water gauge/100 ft.

Therefore, at least one flow =110 cfm, a static pressure = $0.08''$ in the water gauge, and an electric power of one hp are selected according to the flow and static pressure.

The pipe and desired liquid quantity were designed using the Darcy-Weisbach method [26]

According to the water pump specifications, the water flow was 744.822 cm^3/min =45 L/min. Water is used because water is a common scrubbing liquid for removing inorganic contaminants. Water is inexpensive and readily available.

The water tank is designed more than six times to prevent evaporation during the hot, dry summer months. Water was also used to adjust the water-to-air ratio.

Using a tank of approximately 400 liters

The nomograph pipe D = ¾" friction = 1 m/100 m or 1 ft/100 ft was selected.

Mechanical power delivered to the pump

When the pump operates during the wet scrubbing process, an expression for the pumping efficiency described by the equation is used to determine the mechanical power delivered to the pump.

$$P_{pump} = \frac{\Delta \dot{E}}{\eta_{pump}} \quad (12)$$

The electric power of the motor, $P_{electric}$ was obtained by

$$P_{electric} = \frac{P_{pump}}{\eta_{motor}} \quad (13)$$

Then, the system uses one hp water pump and one hp blower.

Then, an air blower with a 1 hp 220 V 50 Hz and a 1 hp 220 V 50 Hz water pump was selected. The selected air blower could provide an airflow of 12.5 m^3/min, while the chosen water pump could provide a water flow of 45 L/min; therefore, the experimental wet scrubber tower could achieve a liquid-to-air ratio of up to 13.21 L/m^3 by using the adjusted inverter to reduce the frequency of the blower.
The prototype of the wet scrubber was constructed as shown in Table 5 and Figure 11.

Table 5 Summary of the Wet Scrubber Tower Design

Parameter	**Numerical Value**
Height of the tower	4 m.
Width of the tower (Square)	0.85 m.
Height of Transfer Unit	2 m.
The spray head	12 pcs
Liquid-to-Air Ratio	Up to 13.21 l/m^3
Pressure Drop of water spray tower	57.13 mm. of the water column
Blower	One hp
Water Pump	One hp
Inlet Diameter	100 mm
Outlet Diameter	150 mm
Parameter	Numerical Value

With this design, we produced a water spray purification tower prototype. The parameters of the four techniques for improving the PM 2.5 removal efficiency were tested.

The following four techniques were used to improve the PM 2.5 removal efficiency of the prototype of the spray wet scrubber:

1. Droplet sizes
2. Water turbulence
3. The packed-bed material
4. Surfactants

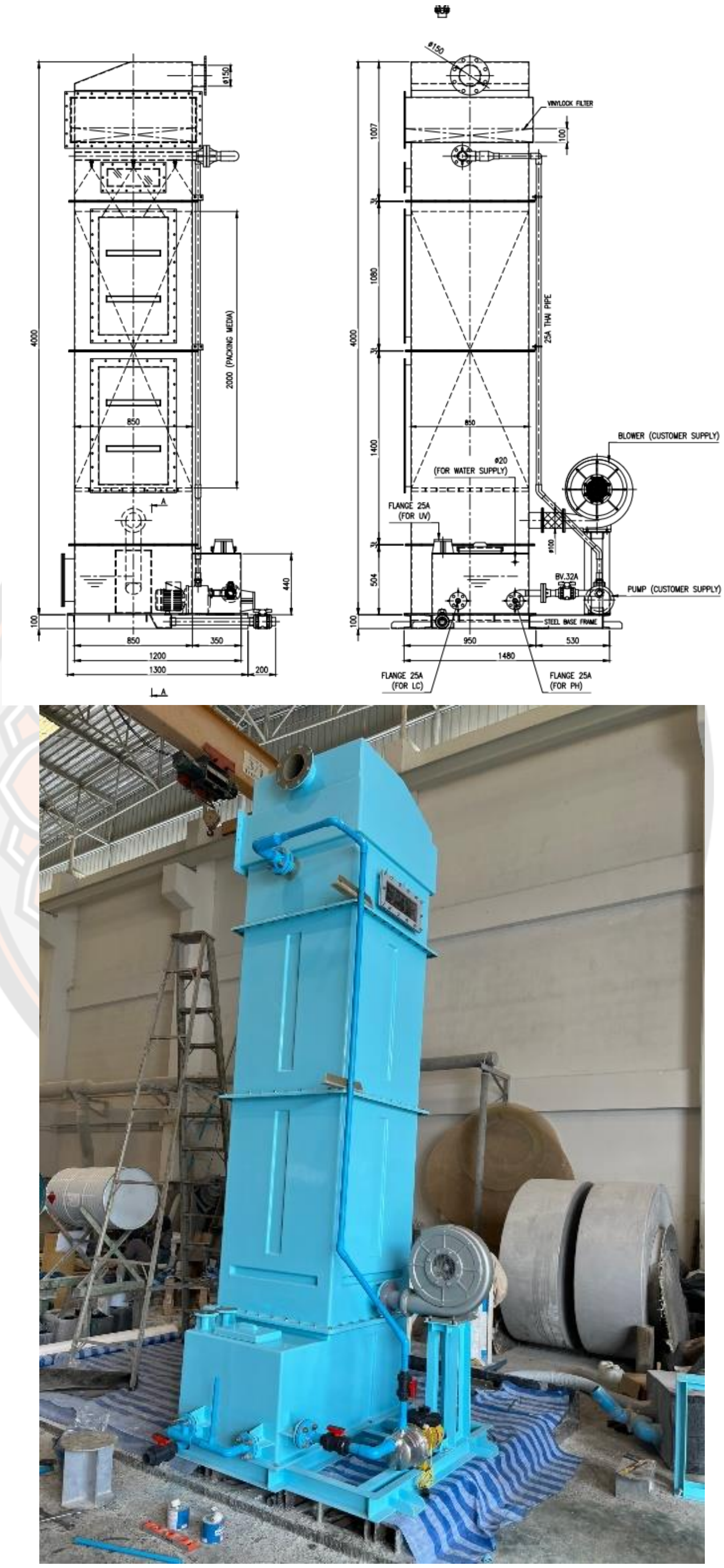


Figure 11 Design and Prototype of the Wet Scrubber Tower

3.2 Changing the Droplet Size in the Absorption Tower

The effect of droplet size was investigated by blowing PM 2.5 and spraying water on three dimensions of droplet size.

A. The mean drop size diameter was 520 µm according to the full cone spray nozzle, the pipe connection size was ¼ inch, the spray angle was 75 degrees, and the spray capacity was 6 l/min at 2 bar. The nozzles were made of stainless steel Model CJJ series (spray code 060 from Inter Spray Co., Ltd, Thailand).

B. The mean drop size diameter was 380 µm when using the full cone spray nozzle, the pipe connection size was ¼ inch, the spray angle was 65 degrees, and the spray capacity was 4 l/min at 2 bar. The nozzles were made of stainless steel Model CJJ series (spray code 040 from Inter Spray Co., Ltd, Thailand).

C. The mean drop size diameter was 270 µm according to the full cone spray nozzle, the pipe connection size was ¼ inch, the spray angle was 55 degrees, and the spray capacity was 0.5 l/min at 2 bar. The nozzles were made of stainless steel Model CJJ series (spray code 005 from Inter Spray Co., Ltd, Thailand).

Plain water was sprayed to eliminate PM2.5 via a fixed water spray at 45 L/min. The airflow speed was reduced from 18 m/s to 7 m/s by using an adjusted inverter to control the blower, and the liquid-to-air ratio increased from 5.14 l/m^3 to 13.21 l/m^3.

3.3 Create and Integrate the Turbulence Box in the Absorption Tower

We operate with plain and turbulent water in the wet scrubber tower by creating a deflector and baffle at the air inlet, with 0 to 150 mm of water high from the nozzle, as shown in Figures 12 and 13.

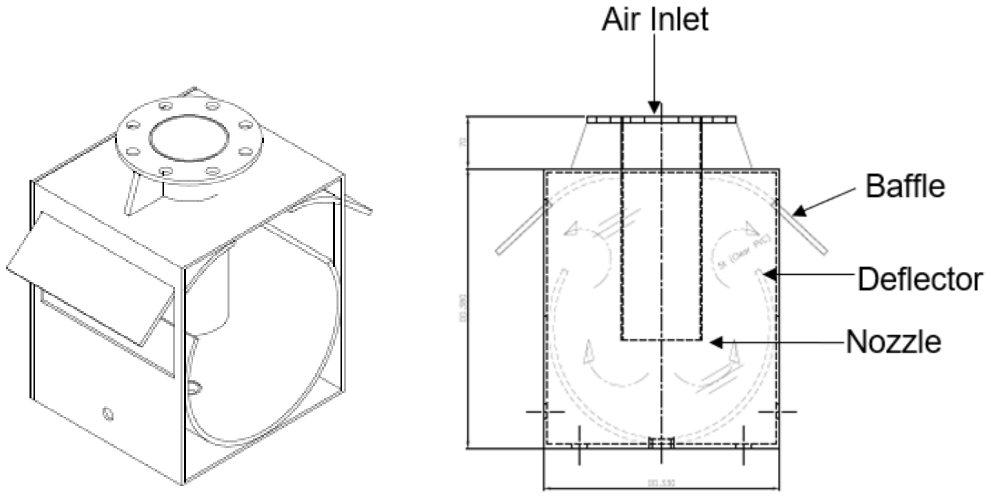


Figure 12 A schematic diagram of the turbulence box in the wet scrubber tower.

This research investigated the turbulent scrubber's PM2.5 removal efficiency at different airflow rates with water heads of 0, 50, 100, and 150 mm above the nozzle. The turbulence box shows that the water level rises from the bottom of the air purification tower, as shown in Figure 13. We test at

1) The water level is 50 mm above the nozzle or 290 mm from the bottom of the prototype, which contains 275 liters of water.
2) The water level is 100 mm above the nozzle or 340 mm from the bottom of the prototype, which contains 323 liters of water.
3) The water level is 150 mm above the nozzle or 390 mm from the bottom of the prototype, which contains 371 liters of water.

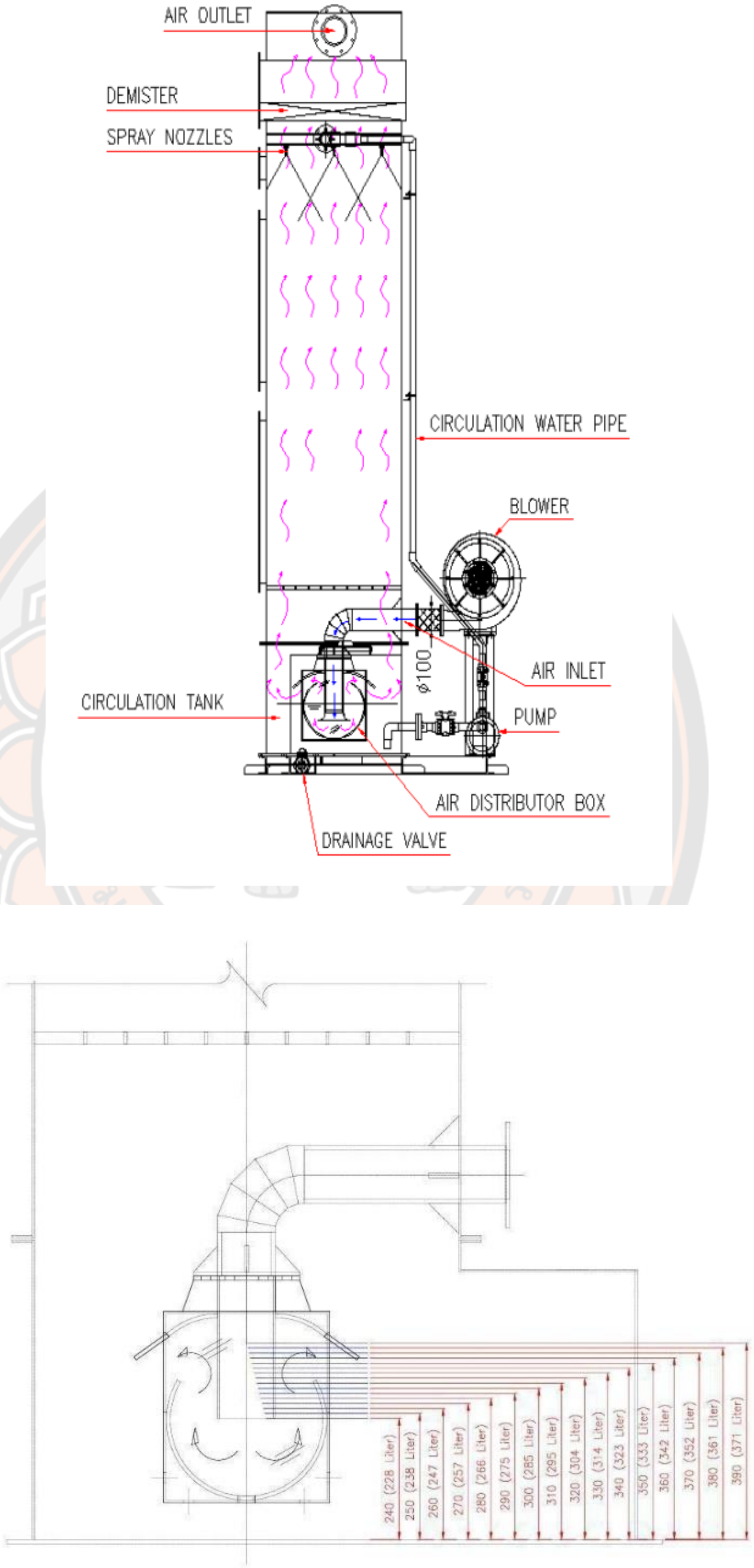


Figure 13 Integration of the Turbulence Water Box in the Wet Scrubber Tower

3.4 Adding the Packed Bed Material to the Hybrid Wet Scrubber Tower

We operated the spray wet scrubber with water turbulence and packed bed material. The experiment was performed by blowing PM 2.5 and spraying water on two types of packed bed material.

Type A: A Pall ring with a random flow configuration has a diameter of 90 mm, a height of 90mm, a specific surface area of 102 m^2/m^3 of media, and a void ratio of 95%. This ring was made of polyethylene from the Aqua Nishihara Corporation, Thailand. This is shown in the Figure 14

Figure 14 Type A: Pall Ring Shape

Type B: A random flow Rasching ring with a diameter of 70 mm, a height of 22 mm, a specific surface area of 190 m^2/m^3 of media, and a void ratio of 90%. This ring was made of polyethylene from the Aqua Nishihara Corporation, Thailand. It is shown in Figure 15.

Figure 15 Type B Rasching Ring Shape

One cubic meter of packed bed was inserted at a time during each experiment by putting the materials above the water tank and the turbulent water system, as shown in Figure 16

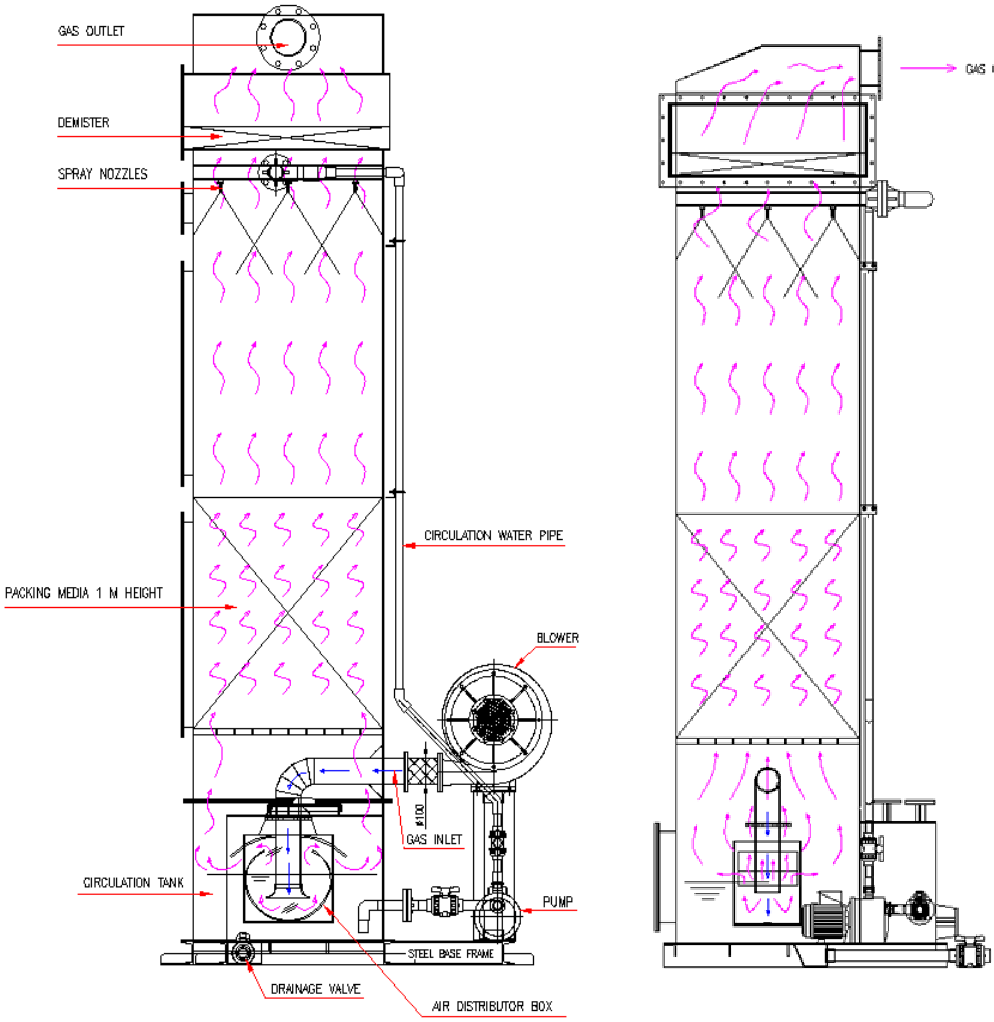


Figure 16 The packed bed material added to the hybrid wet scrubber tower.

3.5 Adding Surfactants into the Hybrid Wet Scrubber Tower

The hybrid wet scrubber was operated with spray water, a turbulence technique, and a surfactant. Then, each surfactant was added to the absorption tower for testing. We control the concentration to be 50 ppm in 371 liters of water and 5 ppm in 371 liters in the turbulent-spray wet scrubber for each type of surfactant.

Then, we added the surfactant at the quantity below.

Condition 1: Test at 50 ppm for each surfactant in the water.

50/1,000,000 = X/(371*1,000)

X = 18.55 grams of surfactant.

Condition 2: Test at 5 ppm for each surfactant in the water.

5/1,000,000 = X/(371*1,000)

X = 1.86 grams of surfactant.

Four types of surfactants for testing;

1) The nonionic surfactant used was a Sobitol monooleate ethoxylated/PANNOX TWEEN 80 from Pan Asia Chemical Corp, Taiwan.
2) The anionic surfactant was sodium lauryl sulfate NEEDLE/RSAW LXNS/ZA from Shanghai Auway Daily Chemicals Co., Ltd., China.
3) The cationic surfactant used was a polyquaternium-22/Resoft 22 from Reachin Chemical Co., Ltd, China.
4) The zwitterionic surfactant was cocamidopropyl betaine/Dehyton® K/I5 from BASF SE, Germany.

3.6 Integrating the IoT System with the Hybrid Wet Scrubber Tower

The experimental absorption tower was integrated with an IoT system for real-time monitoring at the wet scrubber tower's air inlet and outlet to measure the PM 2.5 concentration. The Honeywell HPMA115S0 sensor was selected for this experiment and has proven suitable according to the EPA standard [43, 51]. The HPMA115S0

Sensor is a laser-based sensor that uses the light scattering method to measure the concentration of particles in the range of 0-1,000 µg/m^3. The sensor can provide an accuracy of ±15 µg/ m^3 for a measurement range of 0-1000 µgm^3 at a controlled environmental temperature of 25°C and humidity less than 95%.

We must also install other sensors for the absorption tower, such as airflow, water flow, water level, wind speed, pH, temperature, humidity, and EC sensors. All the sensors send data to the cloud data and application servers, as shown in Figure 17.

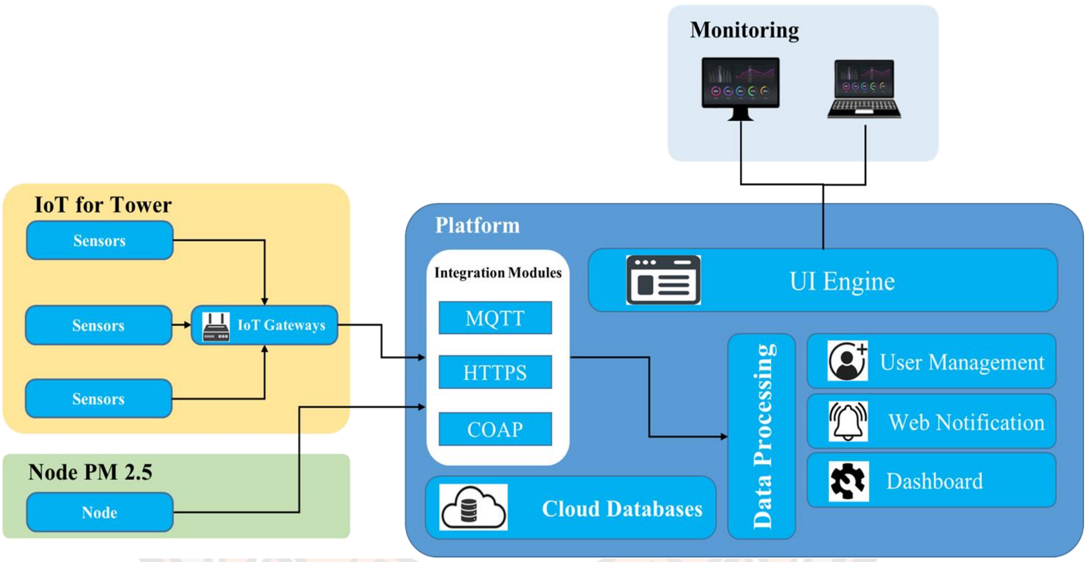
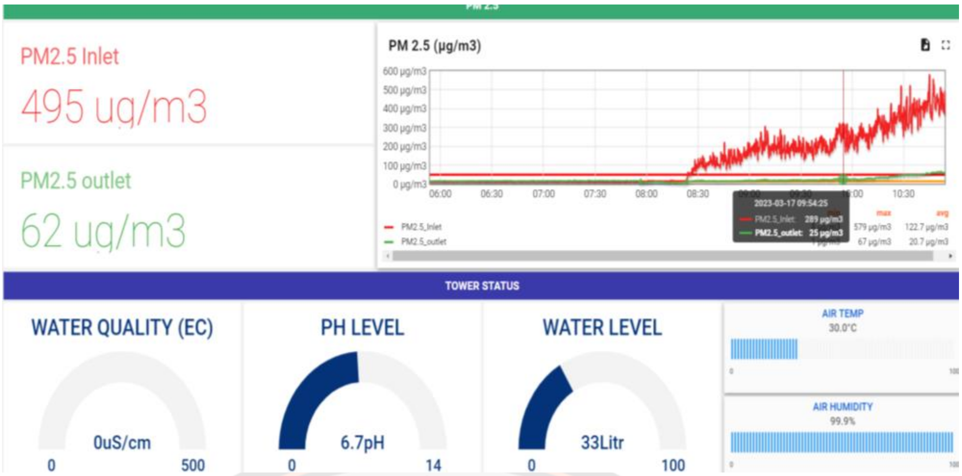


Figure 17 IoT system diagram for the air purification tower

Then, real-time client web monitoring and a cloud server platform were built to collect the data and process the data to monitor the performance of the PM 2.5 absorption tower via the website on a personal computer or mobile device. We can view the data in minutes, hours, days, weeks, and months. as shown in Figure 18.



a) Monitoring via mobile browser

b) Monitoring via PC browser

Figure 18 Real-time monitoring via the a) Mobile Browser and b) PC Browser

3.7 Experimental Room

Indoor experiments

An experimental method for indoor conditions was developed as follows.

1) The 60 m^3 experimental room was built as a controlled environment with polluted air produced from a 10-year-old pickup truck using 2500 cc diesel direct engines.

2) The prototype of the absorption tower integrates an experimental absorption tower with an IoT system for real-time monitoring; this tower is installed at the wet

scrubber tower's air inlet and outlet to measure PM2.5 levels. The Honeywell HPMA115S0 sensor was selected for this experiment. According to the EPA standard, it has proven to be a suitable sensor [44,52]. The HPMA115S0 sensor is a laser-based sensor that uses the light scattering method to measure the concentration of particles in the range of 0-1,000 µg/m^3. The sensor can provide an accuracy between ±15 µg/m^3 for the measurement range of 0 - 1000 µg/m^3 at a controlled environmental temperature of 25°C and humidity less than 95%.

3) The PM 2.5 concentrations at the inlet and outlet were measured over 4 hours per experiment via real-time monitoring. In each experiment, the PM 2.5 dust concentration at the inlet was adjusted from 0 to 500 µg/m^3. The PM 2.5 removal efficiency can be obtained from the formula below.

The PM2.5 average removal efficiency = (mass concentration of PM2.5 inlet – mass concentration of PM2.5 outlet)/mass concentration of PM2.5 inlet x 100%

$$\boldsymbol{\eta_{PM2.5} = \frac{M_{PM2.5,i} - M_{PM2.5,o}}{M_{PM2.5,i}} x100}\% \quad (14)$$

where $M_{PM2.5,i}$ $M_{PM2.5,o}$ and $\eta_{PM2.5}$ are all computed at 15-minute intervals of data from the sensor monitor. $M_{PM2.5,i}$ and $M_{PM2.5,o}$ represent the concentrations of PM 2.5 in the inlet and outlet streams and the area under the curve of the PM 2.5 concentration with respect to the interval time, respectively. The experimental setup is shown in Figure 19, a flow diagram is shown, and Figure 20 shows the real situation.

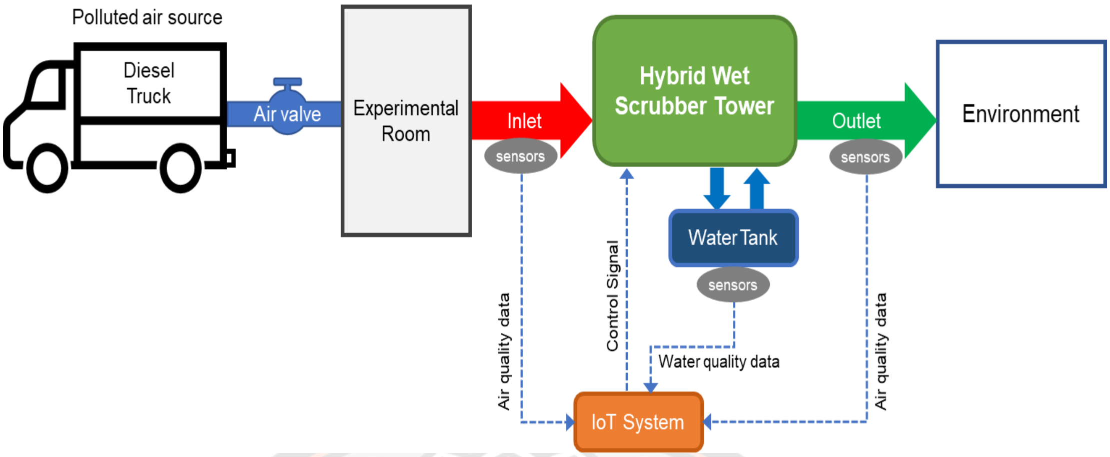


Figure 19 Schematic diagram of the wet scrubber tower with an IoT system and a particle matter sensor connected to the experimental room.

Figure 20 The developed wet scrubber tower installed in the indoor experimental room.

3.8 Computational Fluid Dynamics (CFD) Simulation Software for a Bus Shelter

We used computer fluid dynamics (CFD) simulation software to simulate the effect of clean air from the airflow outlet on the bus shelters in models A and B, which had different airflow outlet pipe system designs, as shown in Figures 21 and 22.

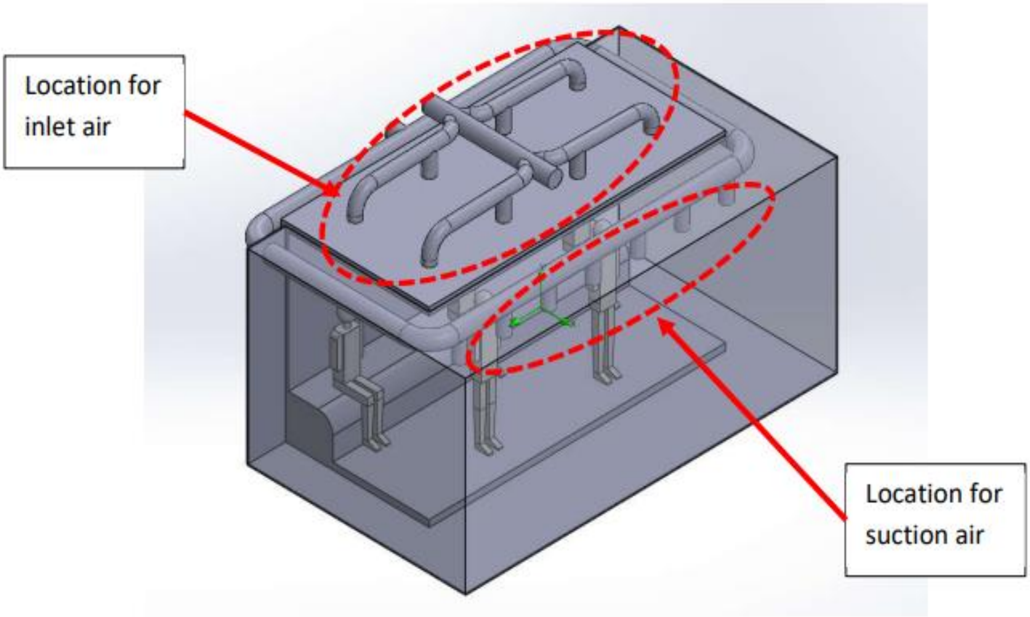


Figure 21 Model A: The design of the airflow outlet pipe system.

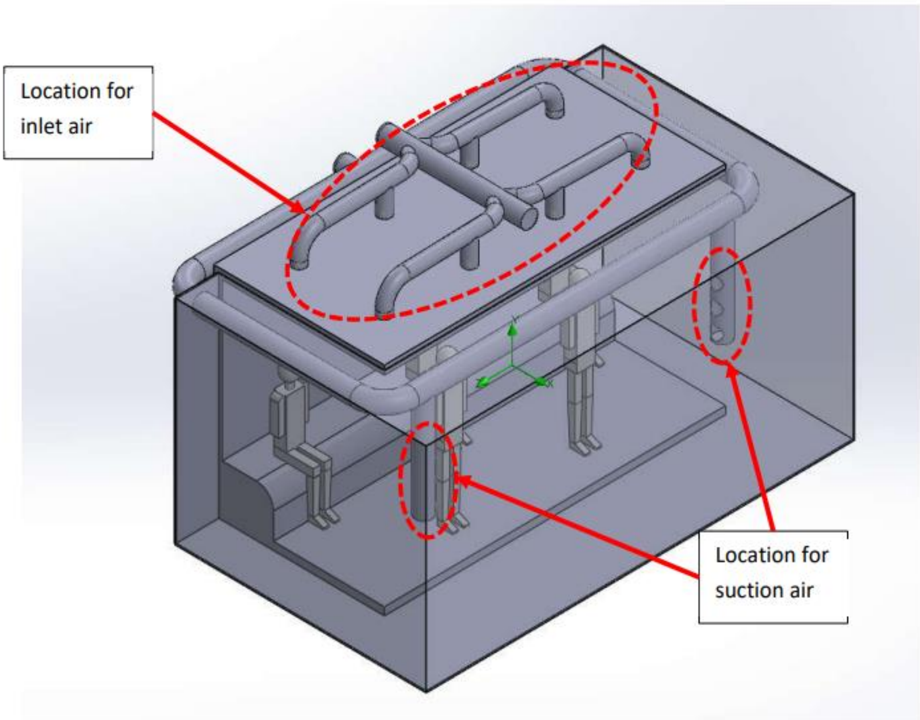


Figure 22 Model B: The design of the airflow outlet pipe system.

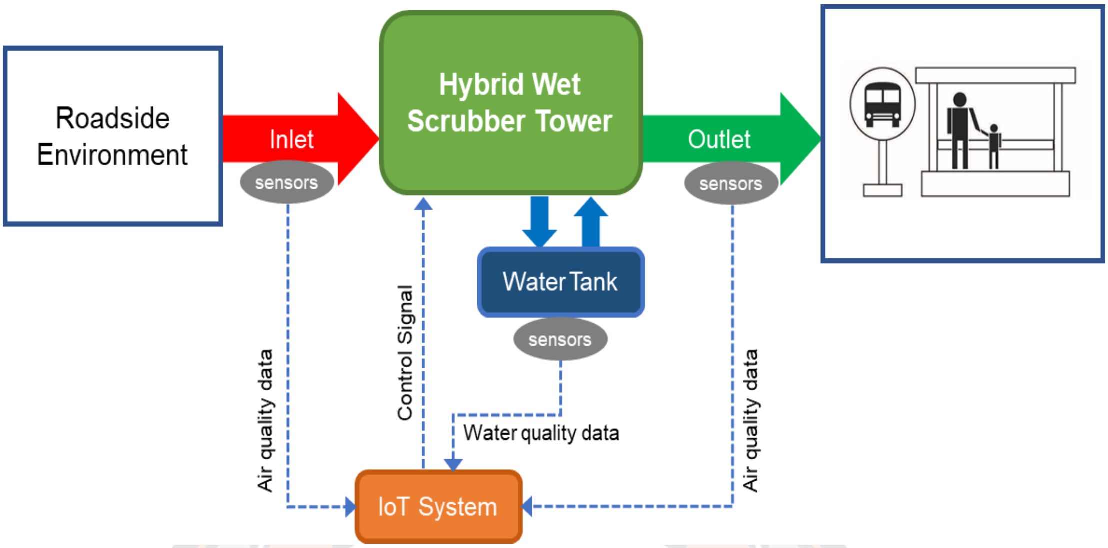
3.9 Outdoor experiment at the Bus Shelter

An experimental method for outdoor conditions was developed as follows.

1) A hybrid wet scrubber tower with an IoT system was installed at the bus shelter.
2) The bus shelter was modified to a semienclosed area by closing the side and back walls, including the roof.
3) The airflow outlet pipe system was installed into the bus shelter.

4) An IoT system controls the wet scrubber tower to operate twice daily (7:00–11:00 AM and 3:00–7:00 PM as busy hours) using the optimum conditions from the indoor experiment.

5) PM 2.5 concentrations at the inlet and outlet of the wet scrubber tower were measured over 4 hours of each operation and computed at 15-minute intervals from the monitoring data. The PM 2.5 removal efficiency $\eta_{PM2.5}$ was calculated using the same method used for the indoor experiment. Figure 23 (a) shows the flow diagram, and 23 (b) shows the real situation.



(a)

(b)

Figure 23 (a) Architecture diagram of the wet scrubber tower with an IoT system for outdoor experiments and (b) the developed wet scrubber tower installed at the bus shelter.

3.10 Collet the Data in the Lab and at the Bus Shelter for Data Visualization.

All the experimental data from the testing room and the bus shelter were subsequently sent to the system and used to summarize the experimental results. The experimental results are presented in the form of summary tables and graphs. The data are stored in a cloud computer for processing, and the results are displayed in

- Hourly graph
- Daily graph
- Weekly graph
- Monthly graph

All the graphs and data can be viewed via mobile phones, tablets, notebooks, or personal computers. All charts and data were subsequently analyzed and used further.

The data collected for the study included the following:

- The concentration of PM 2.5 at the inlet
- Inlet temperature
- Inlet relative humidity
- Concentration of PM 2.5 at the outlet
- Outlet temperature
- Output relative humidity.
- pH value of water
- EC value of water
- The concentration of CO_2 at the inlet and outlet
- The concentration of NO_2 at the inlet and outlet

Remark: The concentrations of NO_2 and CO_2 can be used as indices of traffic density.

CHAPTER IV

RESULTS AND DISCUSSION

In the experiment, the PM 2.5 data were collected from a bus shelter near the road in the center of Phitsanulok municipality during the dry season between January and April 2023, as shown in Figure 24. The results showed that the highest PM2.5 concentration occurred in February, at 223.2 μg/m^3. Then, we set the PM 2.5 concentration from 50 to a maximum of 500 μg/m^3 in each experiment to test the different parameters in the experimental room. In addition to the experiment, PM 2.5 was shown to have a high value between 6:30 a.m. to 8:30 a.m. and during 4:00 p.m. to 6:00 p.m. from the heavy traffic. This can be seen from the CO_2 value shown by the CO_2 sensor from the IoT system, which has increased from 400 to 500-500 ppm during that time.

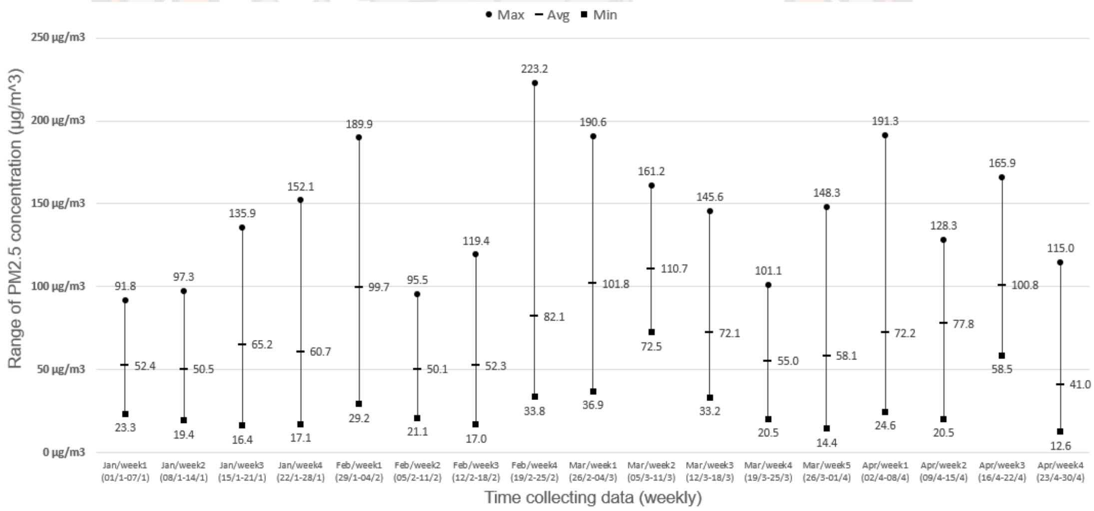


Figure 24 PM2.5 Data were collected from a bus shelter near the road in the center of the Phitsanulok municipality between January and April 2023.

The parameters for PM2.5 removal by a hybrid scrubber tower, such as the liquid-to-air ratio, turbulence created by the water level above the nozzle, water droplet size, packing material, and surfactant, were examined.

4.1 Operating with water and the liquid-to-air ratio

We investigated the PM 2.5 removal efficiency while keeping the flow rate of the spray water constant at 45 l/min using water droplets 270 µm in size. The airflow rate inputs were 8.51, 4.71, and 3.40 m^3 by adjusting the frequency of a one-hp blower by the inverter. The liquid-to-air coefficient, given the values of 5.28, 9.56, and 13.21 l/m^3, comes from fixing the water for the spray part at 45 l/min divided by the air volume, which decreases with decreasing air velocity from adjusting the frequency of the inverter to controlling the blower. The influence of the liquid-to-air ratio on the average efficiency of PM2.5 removal with an air inlet concentration ranging from 50–500 $\mu g/m^3$ is shown in Figure 25, and the average removal efficiency of PM 2.5 is presented in Table 6. The results demonstrated that the average removal efficiency of PM 2.5 when operated using only the spray water scrubbing method was 38.6% at a liquid-to-air ratio of 5.14 l/m^3. However, the average efficiency increased, reaching 58.6% at a liquid-to-air ratio of 13.21 l/m^3. Thus, a lower air flow rate (a lower quantity of PM 2.5) captured more of the PM 2.5 water capacity (still a constant flow rate of 45 l/min). An increasing liquid-to-air ratio resulted in a higher efficiency, which Danzomo [13] also reported. The experiment outcomes were the same as those recommended by the US EPA, with removal efficiencies for particles ranging from 3 to 5 µm in the diameter range of 60-80%. Below 3 µm, the removal efficiencies of the spray scrubbing method decreased to less than 50%[10].

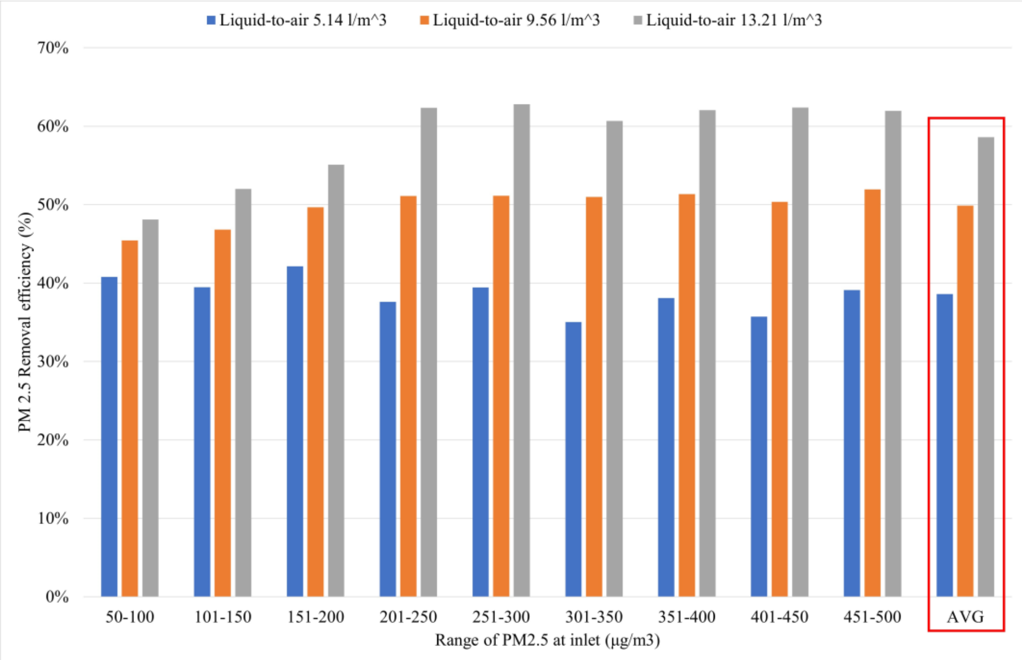


Figure 25 Effect of liquid-to-air ratios of 5.14, 9.56, and 13.21 l/m3 on PM 2.5 removal efficiency with a water droplet size of 270 μm operating with an air inlet concentration range of 50–500 μg/m^3.

Table 6 shows the effect of the liquid-to-air ratio at 5.14 and 13.21 l/m^3 on the PM 2.5 removal efficiency.

Liquid-to-air ratio (l/m^3)	**Average efficiency with spray (%)**
5.14	38.60
9.56	49.86
13.21	58.60

Slower wind speeds at the airflow inlet increase the chance of water droplets and PM 2.5 colliding. This results in a higher water-to-air ratio. However, suppose that this one-hp blower does not have an adjusted inverter. In that case, the removal efficiency of this prototype spray water wet scrubber is 38.6% when it operates under the standard conditions at 50 Hz for one hp blower.

4.2 Effect of Droplet size on PM concentration during absorption

The effect of water droplet size on the average PM2.5 removal efficiency was investigated using a liquid-to-air ratio of 13.21 l/m^3 (with an airflow inlet of 3.4 m^3/min and a water flow rate of 45 l/min). The results are presented in Figure 26 and Table 7. Water droplets of 270, 380, and 520 µm had average PM 2.5 removal efficiencies of 58.63, 53.03, and 38.63%, respectively. Tiny water droplets enhanced PM 2.5 absorption more than larger droplets did, generating more surface contact area and greater absorption capacity. This was in line with the results of Mussatti [28], who reported that smaller droplets captured fine particles as they had a larger surface area-to-volume ratio [28].

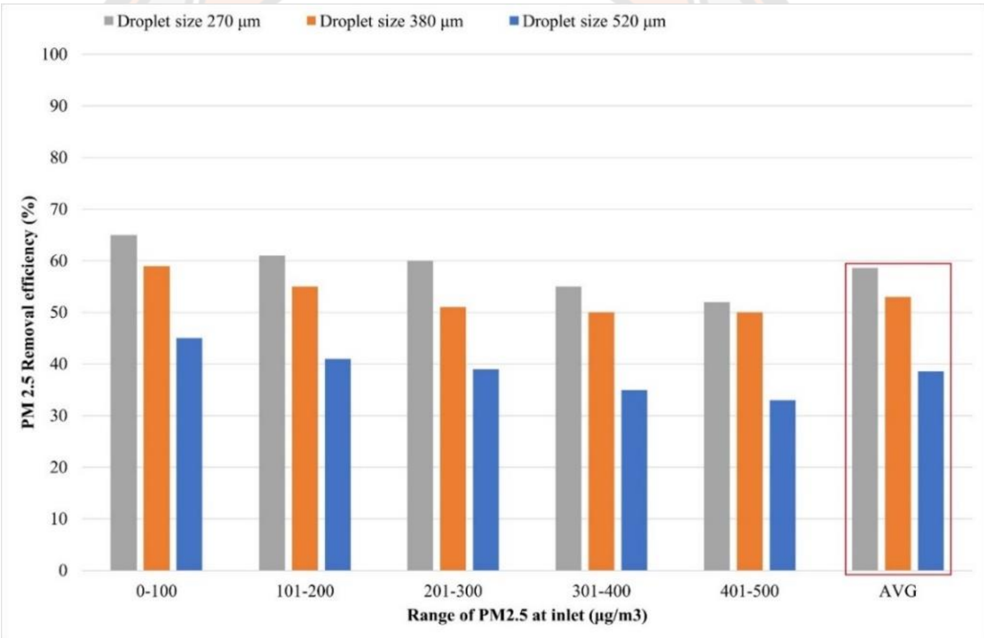


Figure 26 PM 2.5 removal efficiency with different droplet sizes

From these experiments on droplet sizes, we selected to use a droplet size of 270 microns in our wet scrubber prototype in the spray section. The spray section provides a PM 2.5 removal efficiency of nearly 60%, according to Table 7, depending on the airflow speed, liquid-to-air ratio, and concentration of PM 2.5 from the airflow inlet.

Table 7 The average efficiency of PM2.5 removal is based on water droplet size.

Mean droplet diameter (μm)	PM2.5 removal efficiency (%)					Avg (%)
	0–100	101–200	201–300	301–400	401–500	
270	65.2	61.12	60.03	55.15	51.65	58.63
380	58.96	55.14	51.05	49.89	50.1	53.03
520	45.12	40.16	39.43	35.31	33.11	38.63

4.3 Effect of Turbulence on PM concentration during absorption

Turbulent water in this spray-wet scrubber tower was achieved by installing a deflector and baffle (Figure 27) at the airflow inlet. Moreover, the water level above the nozzle was varied (50, 100, or 150 mm) by keeping the spray water at 45 l/min. In this study, turbulence was coupled with spraying water droplets, and PM 2.5 absorption was expected at the droplets and deflectors.

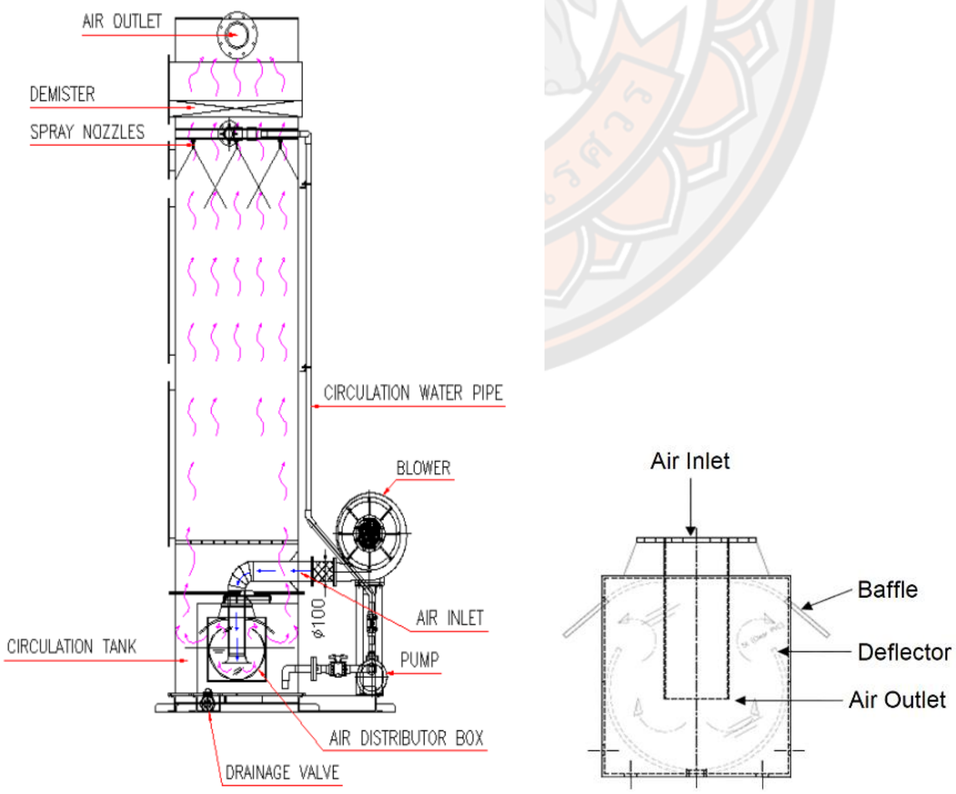


Figure 27 A schematic diagram of the turbulence wet scrubber system.

The deflector and baffle reduced the airflow velocity via the water's airflow resistance and increased the efficiency of PM 2.5 removal. The average efficiency of PM 2.5 removal as a function of inlet PM 2.5 concentration in the 50-500 µg/m3 range and different water levels above the nozzle are compared with and without spraying water and presented in Table 8, Figure 28. During operation, a pressure drop was observed from 155.45 to 223.25 mm H_2O with a 0–150 mm water level, as shown in Table 8. This pressure drop was created by airflow resistance from the water above the nozzle. Using only turbulence without spraying water had average efficiencies of 42.83%, 59.67%, 66.03, and 71.56% at 0, 50, 100, and 150 mm of water levels above the air outlet, respectively, as shown in Figure 28.

In contrast, using turbulence with spray water produced average efficiencies of 48.55%, 71.12%, 80.83, and 87.59% for 0-, 50-, 100-, and 150-mm water above the air outlet, respectively, as shown in Figure 28. Adding water spray absorption to the turbulence technique enhanced the PM2.5 removal efficiency. In particular, higher water levels created a greater difference in average efficiency between turbulent and coupled turbulence conditions with spraying water, which was 16% at a water level of 150 mm. The airflow speed was reduced by the airflow resistance of water above the air outlet, which also helped to increase the liquid-to-air ratio from 5.14 to 9.03 l/m^3 in the spray section. This could be explained by the fact that more water above the air outlet caused a longer residence time of absorption, resulting in greater PM 2.5 removal.

Therefore, increased PM2.5 removal efficiency was observed with rising water levels, as shown in Table 8 and Figure 28. This result was observed in previous studies [17-21].

Table 8 Increasing liquid-to-air ratio as a function of the water level above the nozzle.

Water level (mm)	Liquid-to-air ratio (l/m^3)	Pressure drops. (mm H_2O)	Average efficiency: only turbulence (%)	Average efficiency: Turbulence with spraying water (%)
0	5.14	155.45	42.83	48.55
50	6.38	175.97	59.67	71.12
100	7.26	204.99	66.03	80.83
150	9.03	223.25	71.56	87.59

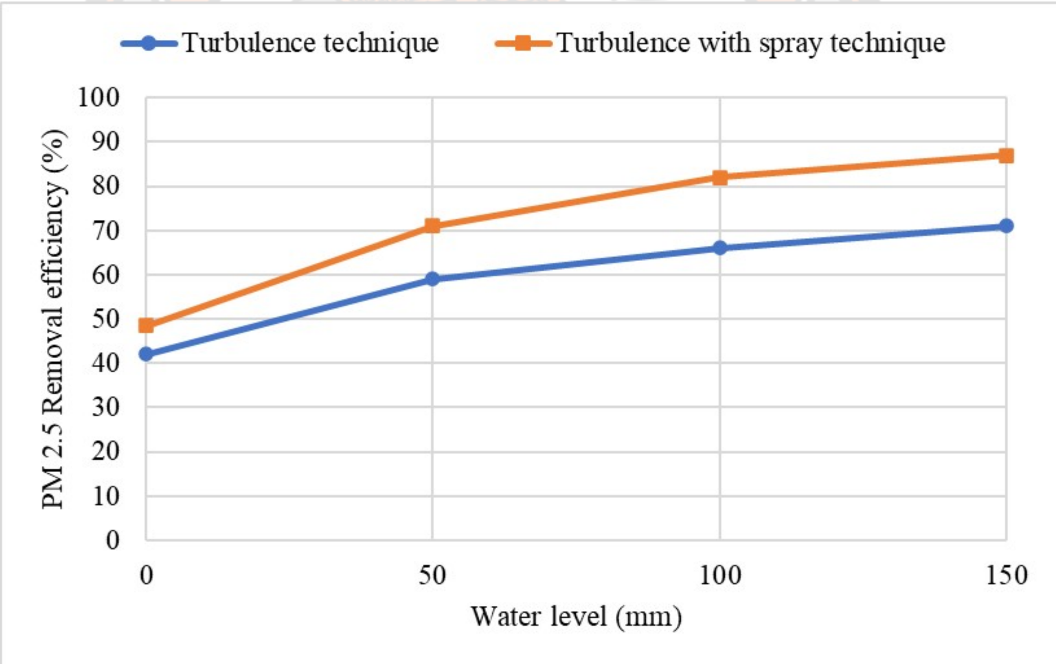


Figure 28 Comparison of PM 2.5 removal efficiency for only turbulence and only turbulence with spray water.

Moreover, the PM 2.5 concentration output during the operation of spraying water with turbulence at a water level of 150 mm (with a PM 2.5 inlet not exceeding 250 μg/m^3) was less than 15 μg/m^3, which met the WHO guidelines for PM 2.5

intensity. Figure 29 shows the PM 2.5 removal using turbulence with a water level of 150 mm operating with water spraying, which produced the highest efficiency. Figure 29 also shows the average removal efficiency and PM 2.5 outlet concentration at an inlet ranging from 50–500 μg/m^3. The PM 2.5 outlet concentration increased as the inlet concentration increased. The average efficiency remained in the 85-92% range, whereas the outlet concentration increased from 9.88 to 14.62 μg/m^3, and the inlet concentration increased from 50 to 250 μg/m^3.

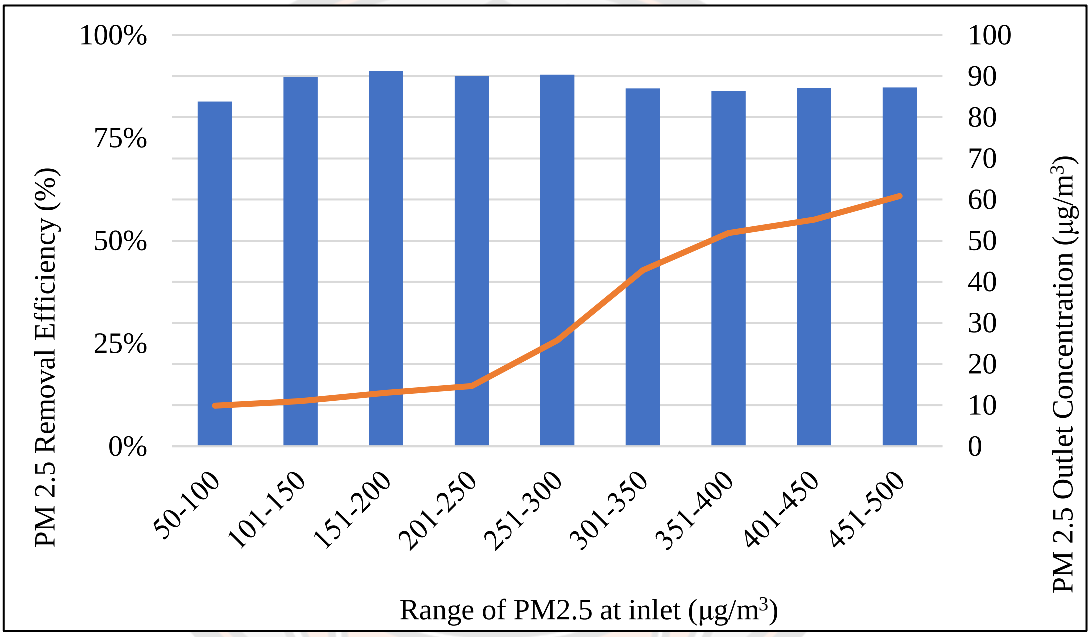


Figure 29 Effect of a water level of 150 mm on the average PM 2.5 removal efficiency and PM 2.5 outlet concentration when operating with water spraying.

Pressure loss for the turbulent water system

Adding the turbulence box to the proposed wet scrubber tower, which has a higher level of water at the nozzle, increases the pressure loss in the wet scrubber tower, as shown in Figure 30. Turbulence will dramatically change the behavior of the tower at approximately the level of water above the nozzle, as shown below:

$$\Delta P = \sum_{i=1}^{n} Pi \tag{15}$$

$$\Delta P = P_1 + P_2 + P_3 + P_4 + P_5 + P_6 \qquad (16)$$

Pressure loss for straight duct, $\Delta Ps = f\ L/d\ pV^2/2g$

Pressure loss for miscellaneous parts (fitting, valve, elbow, etc.), $\Delta Pm = kpV^2/2g$

Pressure loss due to the water level, $\Delta Pz = \Delta Z$

where f = friction loss for straight duct (-)

L = length of duct (m)

d = duct diameter (m)

p = Gas density (kg/m^3)

V = gas velocity (m/s)

g = gravity (m/s^2)

k = loss coefficient of the miscellaneous part (-)

Z = Height level (m)

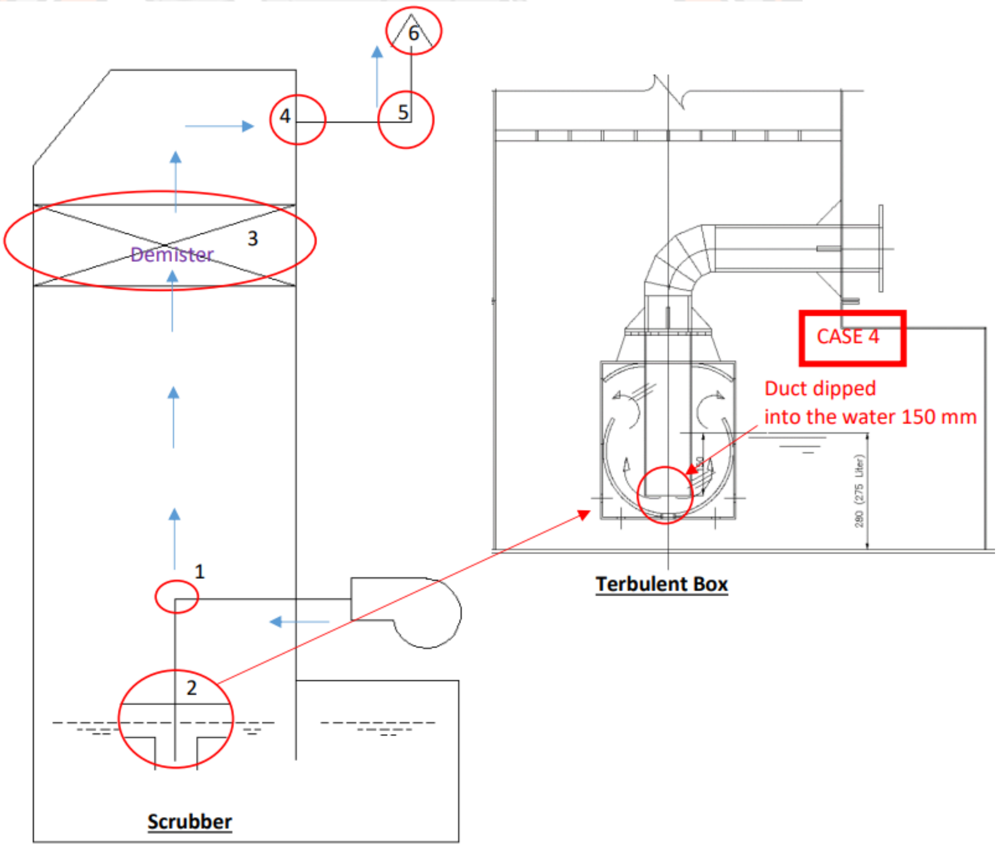


Figure 30 Pressure Drops in the Hybrid Wet Scrubber

The total result of the pressure drop is shown in Table 9.

Table 9 The calculation of the total pressure drop.

Gas flow rate for the exhaust fan = 9.6 m^3/min

Point	Position	Equation Source	Duct size (mm)	Gas velocity in duct (m/s)	Pressure loss (mmH_2O)
1	Elbow 90°	$kpV^2/2g$	Æ100	20.37	20.31
2	Turbulent box	$kpV^2/2g$ +DZ	-	20.37	190.61
3	Demister	Demister data	850Wx850Lx100H	0.22	0.30
4	Outlet	$kpV^2/2g$	Æ150	9.05	4.01
5	Elbow 90°	$kpV^2/2g$	Æ150	9.05	4.01
6	Stack cover	$kpV^2/2g$	-	9.05	4.01
		Total pressure drop			223.25
					~2200 Pa

Note:

1* The straight duct and flexible duct pressure loss are negligible

2* The gas velocity at the stack cover is based on the maximum value of stack discharge.

3* The pressure drop of the demister is the data from the Vinylock filter used for the demister of the scrubber.

4* The pressure drop in the turbulent box is equivalent to 2 sets of elbow 90 s° due to flow the direction.

Combined with the water level at which the duct was dipped in water, as shown in the turbulent box above.

5* The pressure drop at the scrubber outlet (No.4 in Figure 30) is equivalent to that at elbow 90° due to the flow direction

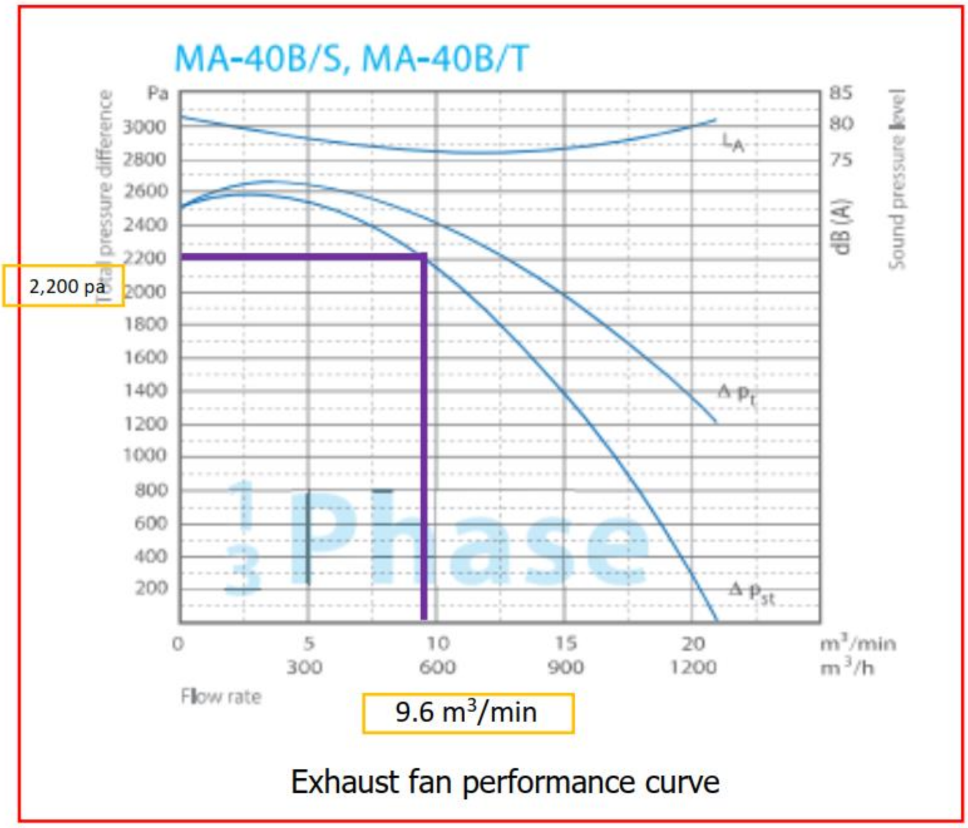


Figure 31 Effect of pressure drop on exhaust fan performance.

When trial and error occur for various fan flow rates, the scrubber system pressure drops by approximately 2,200 Pa, given the maximum gas flow rate of 9.6 m^3/min, as shown in the performance curve of the exhaust fan in Figure 31.

Adding the turbulence box to the proposed wet scrubber tower, with a higher level of water at the nozzle (0-150 mm), which increases the pressure loss in the wet scrubber tower, will make a dramatic change to the behavior of the tower about the level of water above the nozzle as shown in Table 10 and Figure 32.

Table 10 Pressure drop changes when the water level above the nozzle changes.

Conditions	Pressure drops (mm H2O)
Spray water only (No turbulence)	69.08
Water level above nozzle = 0 mm	155.45
Water level above nozzle = 50 mm	175.97
Water level above nozzle = 100 mm	204.99
Water level above nozzle = 150 mm	223.25

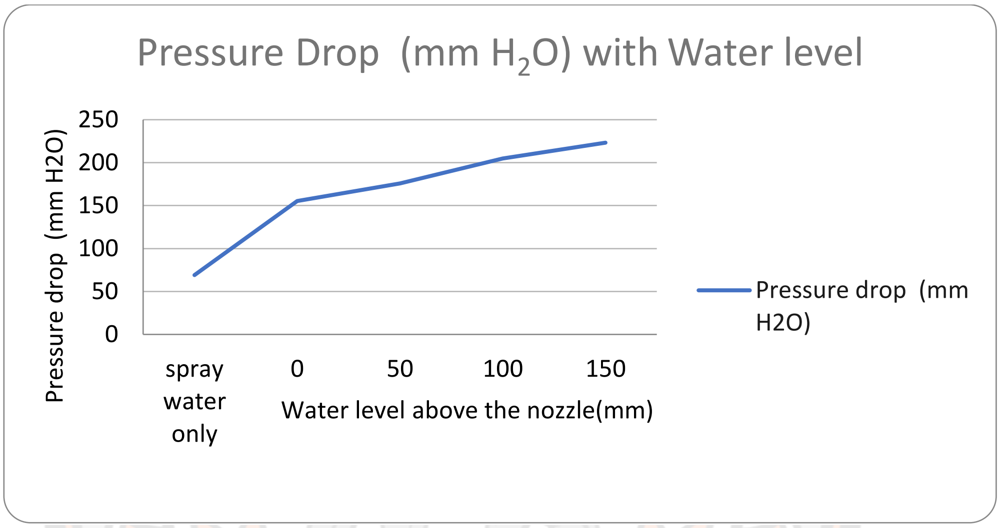


Figure 32 Pressure drop increases following the increase in the water level above the nozzle.

A significant pressure drop from the air resistance from creating turbulent water occurs. Even though this increases the PM 2.5 removal efficiency, more energy is needed, and less air is produced.

4.4 Effect of the packed bed on the PM concentration during absorption

The packing material was expected to promote PM2.5 absorption due to the increased contact surface area and time between the air and water. We used two packing materials: a Pall ring (A) with a specific surface area of 102 m^2/m^3 of media and a Raschig ring (B) with 190 m^2/m^3 of media. An absorption tower of each type was used to fill approximately the same surface contact area of 100 m^2. The average PM 2.5 removal efficiencies with spraying water only, spraying water, and packed bed type A and spraying water and packed bed type B were 58.63% , 53.03% , and 52.31% , respectively, as shown in Table 11 and Figure 33. No improvement was found after adding packing material. The efficiency of using both types of packing material was approximately the same but was approximately 5% lower than that of not using both materials. The function of both kinds of packing material was to decelerate the droplets with barriers in the packing material, and the droplets merged to form larger droplets when they hit the obstacles, resulting in a decrease in the contact surface area between the air and water. The US EPA [10, 30] suggests that packed-bed scrubbers are more suitable for gas scrubbing than for PM scrubbing, as accessing, cleaning, and changing spray heads are more challenging in bed clogs and plugging. A packed-bed wet scrubber can be used for low dust-loading applications and for particulate matter larger than 5 µm [10, 30].

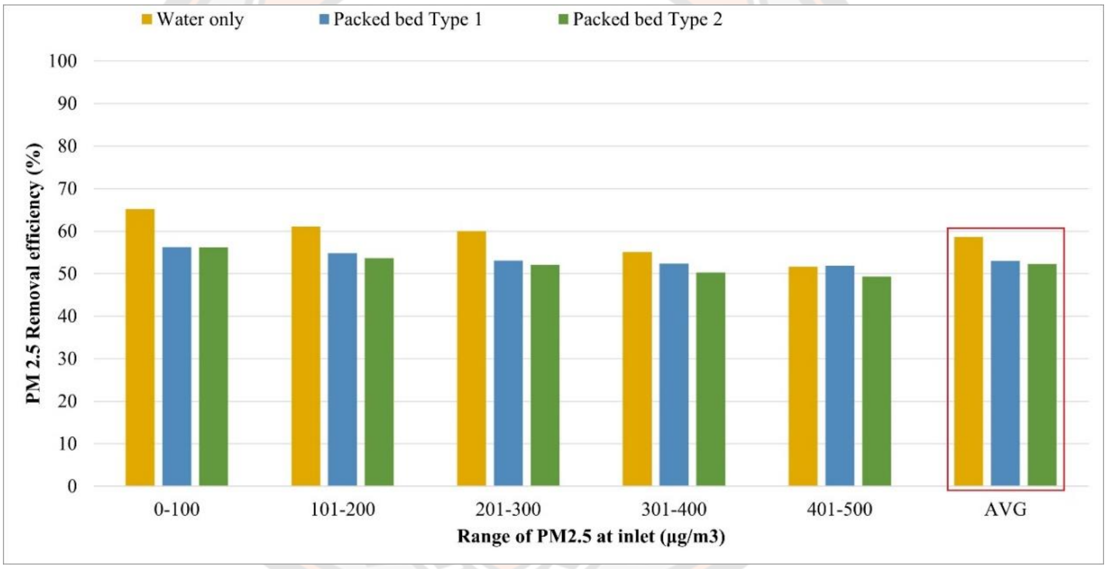


Figure 33 Effect of the packed bed on the average efficiency of PM 2.5 removal.

Table 11 Effect of the packed bed type.

Experiment Condition	**PM2.5 removal efficiency (%)**					**Avg (%)**
	0–100	**101–200**	**201–300**	**301–400**	**401–500**	
Spraying water only	65.2	61.12	60.03	55.15	51.65	58.63
Spraying water and packed bed type A	56.25	54.82	53.08	52.36	51.85	53.03
Spraying water and packed bed type B	56.19	53.66	52.12	50.26	49.33	52.31

We also faced bed clogs and plugging, which are more challenging to access, clean, and change the spray heads during testing, as shown in Figure 34.

Blocking the spray head with packed bed material reduces the liquid-to-air ratio and allows air to pass through the chamber without colliding with water droplets. This causes the purification tower to be less efficient.

Figure 34 Figure 35 The packed bed material clogs the spray heads.

4.5 Effect of Surfactants during Absorption

When each of the four types of surfactants was added in each experiment in a ratio of 5 ppm or 50 ppm, the experiment could not be completed because of excessive foaming inside the purification tower, causing the blower to stop working, as shown in Figure 35.

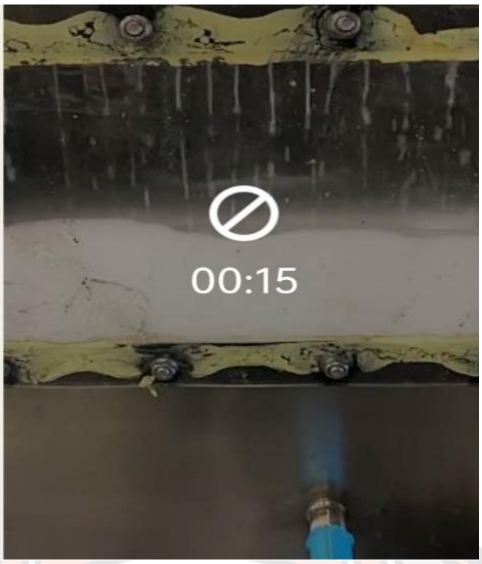


Figure 36 Excessive foaming inside the Hybrid Wet Scrubber Tower

4.6 The Results from the Experimental Room for the Hybrid Wet Scrubber

After testing the four techniques, we used a water spray and turbulence water systems to propose a hybrid wet scrubber to remove PM 2.5. We tested the 900 µg/m3 dust concentration according to the sensor specifications. A droplet size of 270 microns was used in the absorption tower. Turbulence techniques create water turbulence in this spray wet scrubber tower by installing a deflector and baffle at the airflow inlet and varying the water level above the nozzle by maintaining the initial liquid-to-air ratio at 5.14 l/m^3, which reduces the airflow velocity through the airflow resistance of water and increases the efficiency of PM 2.5 removal. The average efficiency of PM 2.5 removal as a function of the inlet PM 2.5 concentration ranges from 50-900 $\mu g/m^3$, and different water levels above the nozzle are shown in Figure 36. The effect of turbulent-spray water showed that the average efficiency of PM 2.5 removable was more than 70% by 50 mm of water above the nozzle, more than 80% by 100 mm of water above the nozzle, and more than 85% by 150 mm of water above the nozzle, as shown in Figure 36. The airflow speed was reduced by the airflow resistance of water above the nozzle to create stirring water. Therefore, when the airflow speed decreases, the liquid-to-air ratio in the spray part increases, as shown in

Table 12. Then, the airflow outlet of the hybrid wet scrubber was reduced from 7 to 5 CMM, as shown in Table 13.

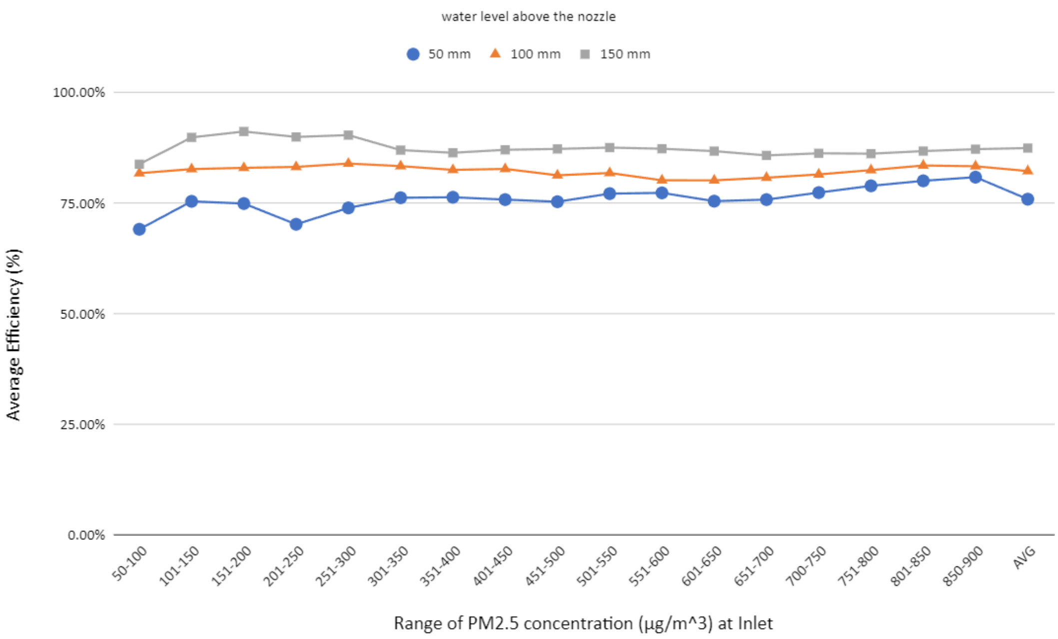


Figure 37 PM 2.5 Removal efficiency of the hybrid wet scrubber at water levels above the nozzle of 50, 100, and 150 mm

Table 12 Average efficiency of the hybrid absorption tower with increasing liquid-to-air ratio as a function of the water level above the nozzle

The water level above the nozzle, mm	Liquid-to-air ratio l/m^3	Average efficiency %
0	5.14	30.4
50	6.38	71.7
100	7.26	80.8
150	9.03	87.3

Table 13 Air Volume of Hybrid Absorption

Water level (mm) above the nozzle	Airflow at inlet (m/s)	Air volume (m^3/min)
50	14.5	7.05
100	12.75	6.2
150	10.25	4.99

The effect of turbulent water or the bubble part had an efficiency of PM 2.5 removal higher than 80% according to experimentation in the laboratory test at an airflow of 4.99-6.2 CMM with 100-150 mm water above the nozzle.

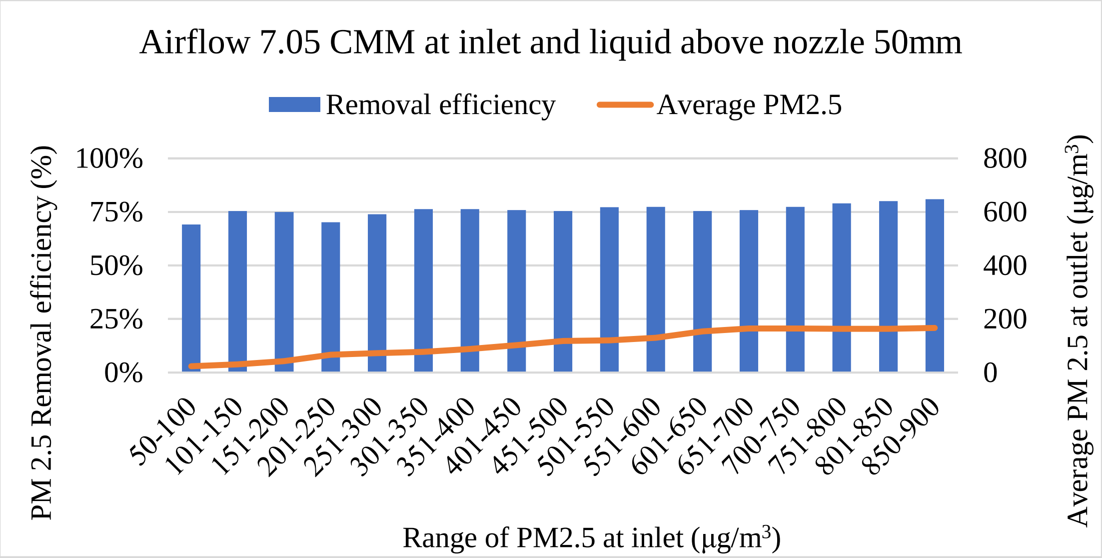


Figure 38 Effect of the 50 mm water level on the average PM 2.5 removal efficiency and PM 2.5 outlet concentration when operating with water spraying.

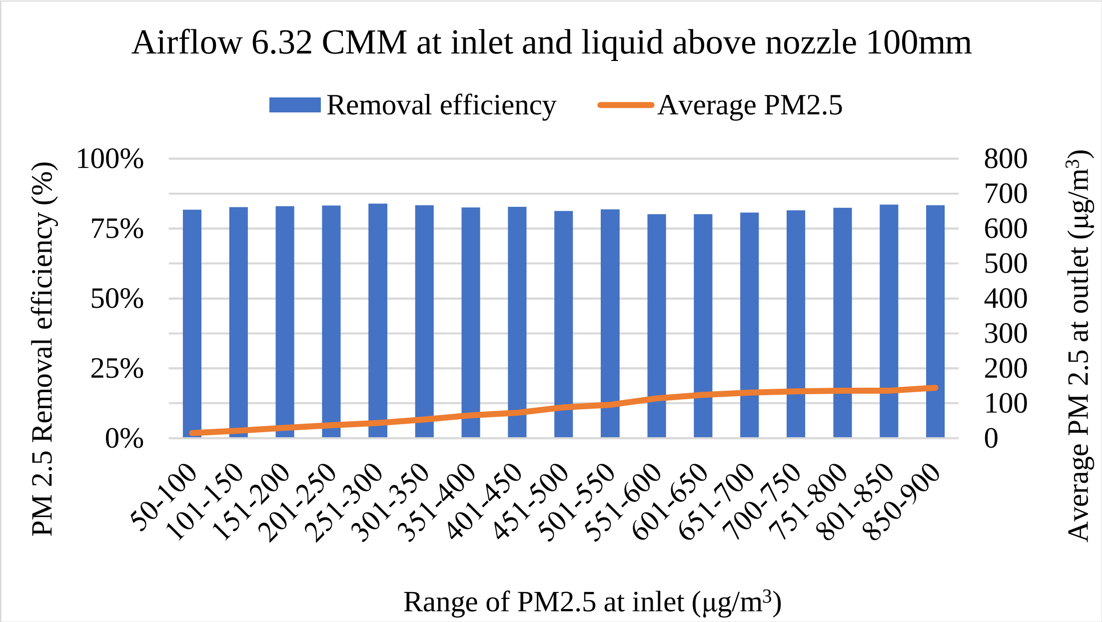


Figure 39 Effect of 100 mm water level on the average PM 2.5 removal efficiency and PM 2.5 outlet concentration when operating with water spraying.

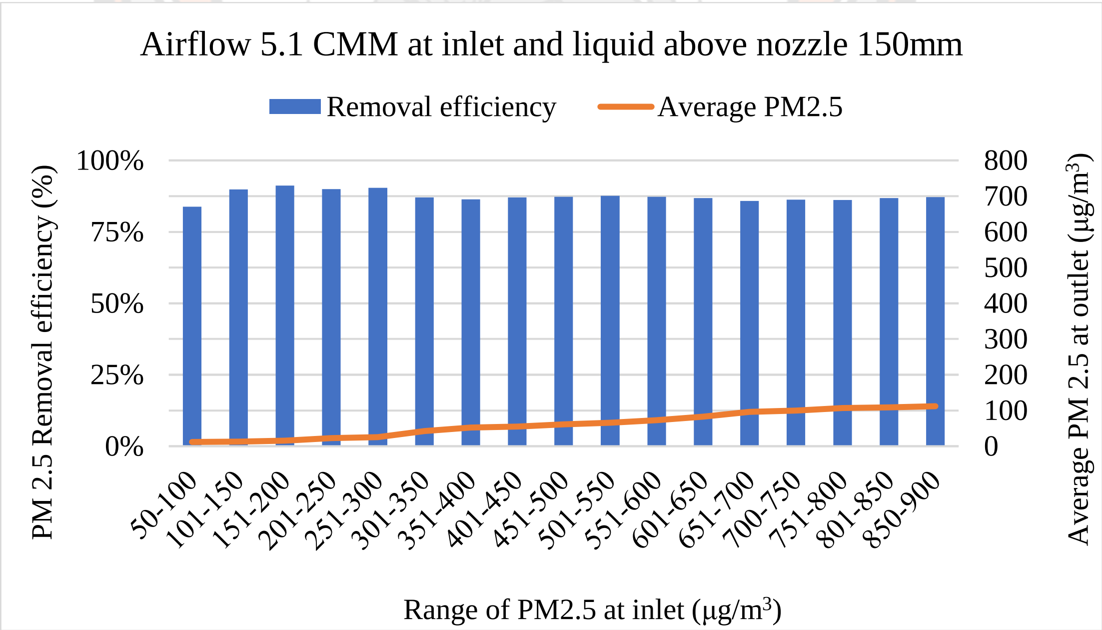


Figure 40 Effect of 150 mm water level on the average PM 2.5 removal efficiency and PM 2.5 outlet concentration when operating with water spraying.

Experiments were conducted at the concentration of PM 2.5 not exceeding 500 µg/m^3. It was found that the dust removal efficiency was more than 80%. The dust was able to be reduced to meet the standards of the Pollution Control Department of Thailand when the PM 2.5 concentration in the ambient environment was not more than 350 µg/m^3 and met the standards of the WHO when the PM 2.5 concentration in the ambient environment was not more than 250 µg/m^3.

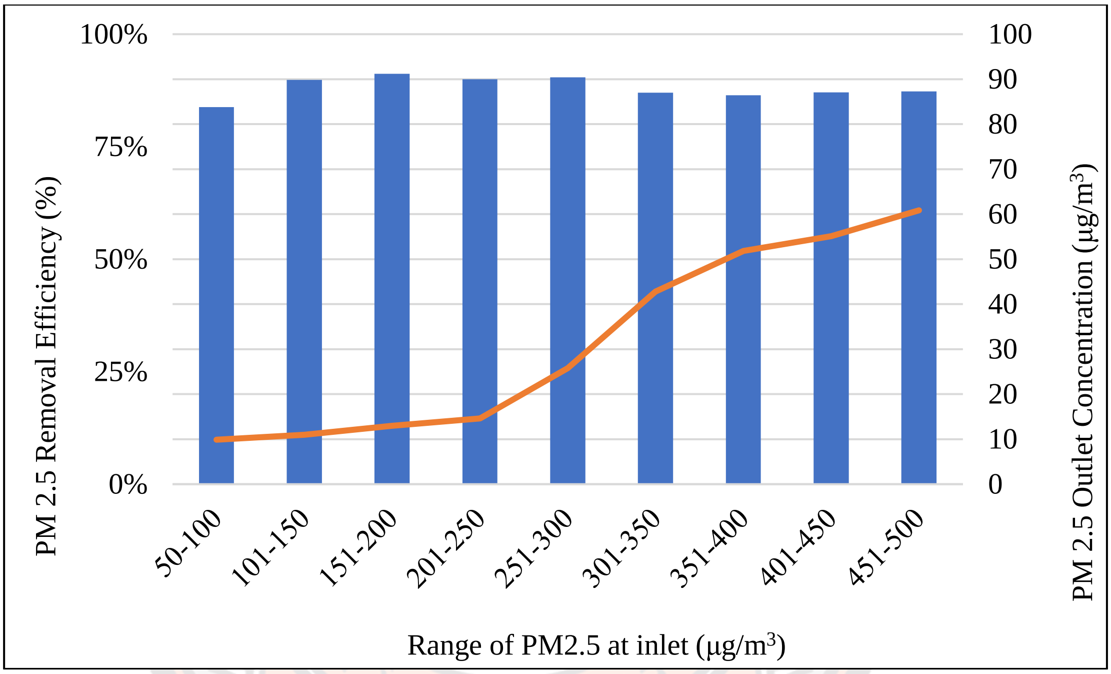


Figure 41 Effect of the 150 mm water level on the average PM2.5 removal efficiency and PM2.5 outlet concentration when operating with water spraying.

4.7 The Results from the CFD program for the bus shelter

Air velocity in the web scrubber

The airflow velocity and residence time were studied. The wind speed in the airflow pipe system decreases from 10.25 meters per second (5 CMM) down to 0.15 meters per second when moving through the air purification tower, or what is called the residence time. The longer the residence time is, the greater the chance of dust particles colliding with water droplets.

$$V = \frac{Q}{A} = \frac{Q}{(W \times L)}$$

V: Air velocity (m/s)

Q: Air flow rate (m^3/s)

A : Cross-sectional area (m^2); A = W x L

W: Width of scrubber (m)

L: Length of scrubber (m)

Then, Air flow rate, Q = 5 m^3/min

Scrubber Width, W = 0.85 m

Scrubber Length, L = 0.85 m

Cross-sectional area, A = 0.7225 m^2

$$\text{Air velocity, } V = \frac{Q}{60 \times A}$$

$$= \frac{5}{0.7225} \frac{m^3/min}{m^2} \times \frac{1 \ min}{60 \ s}$$

$$= 0.115 \ m/s$$

Air velocity in scrubber size (850 mm x 850 mm) is 0.115 m/s, or Air takes approximately 35 seconds or more than half a minute to move in a 4-meter height of the air purification tower.

The CFD results showed that laying out the B-style air duct system was better than laying out the A-style one because it is better to create an air curtain from the air outlet, and the wind speed at the bus stop should not exceed 5-6 meters/second.

A-Style air duct system

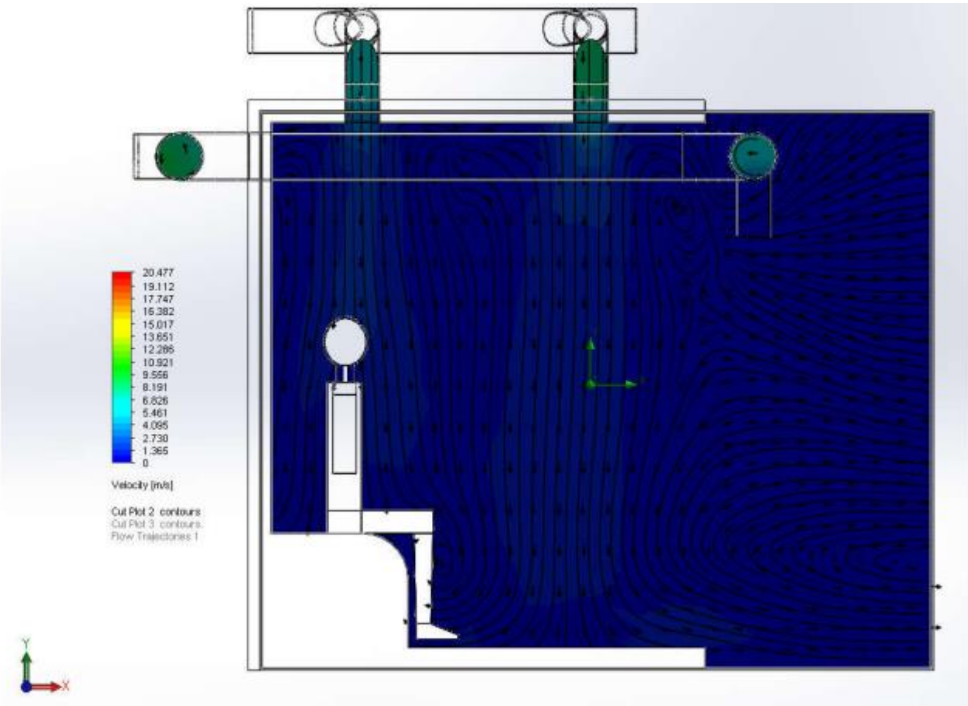


Figure 42 Elevation view of Model A

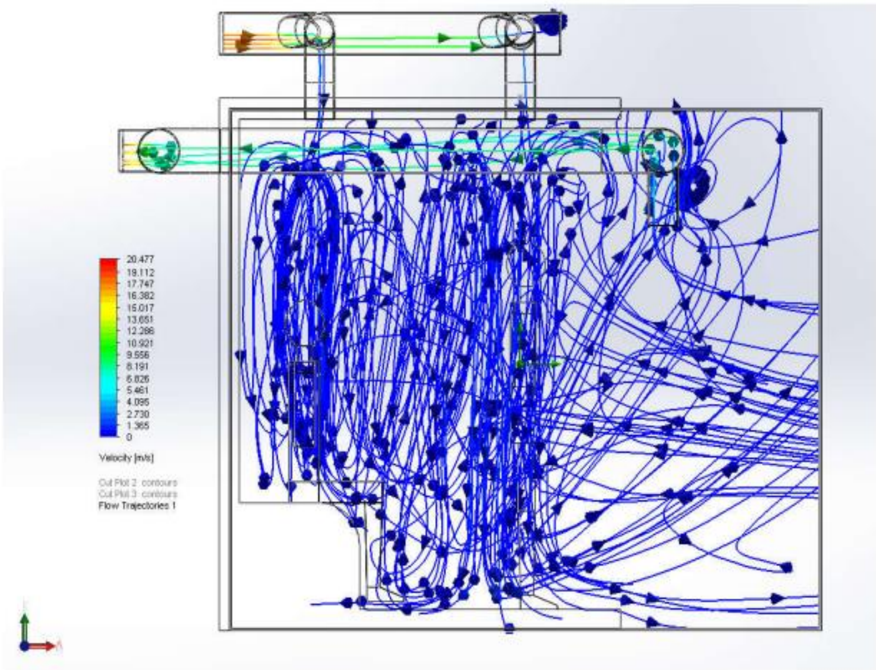


Figure 43 Elevation view of Model A

B-style air duct system

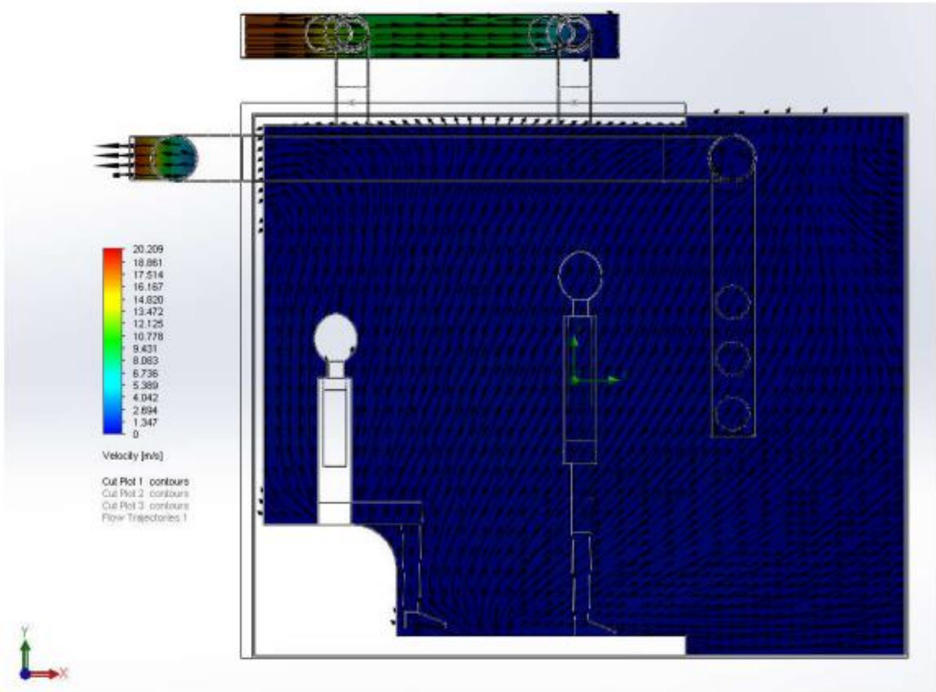


Figure 44 Elevation view of Model B

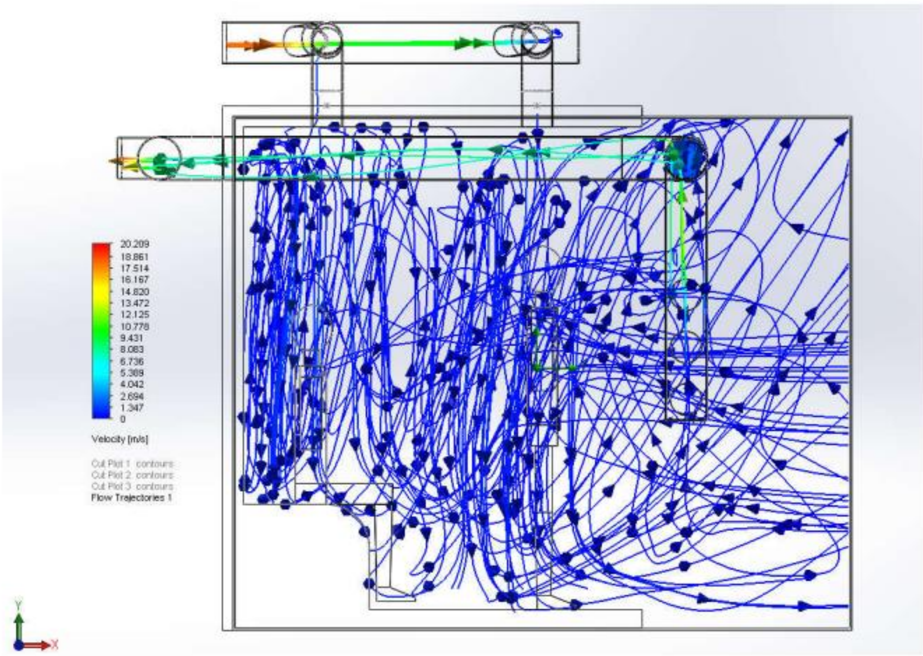


Figure 45 Elevation view of Model B

4.8 Performance of the proposed hybrid wet scrubber tower installed at the bus shelter for the outdoor experiment.

In April, the hybrid wet scrubber was operated at an airflow rate of 4.99 CMM and 150 mm of water above the nozzle at the bus shelter. The average PM 2.5 concentrations of the air purification tower in the inlet and outlet are shown in Figure 45. The method also performed excellently by revealing the value of clean air at an airflow outlet concentration that met the World Health Organization (WHO) or the Pollution Control Department of Thailand (PCD) standards throughout the month.

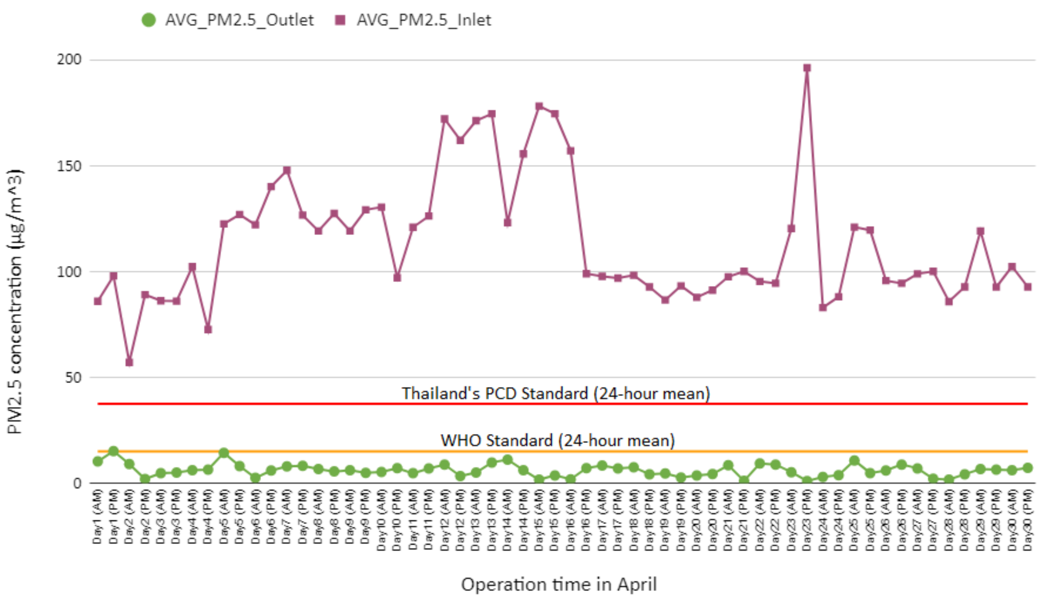
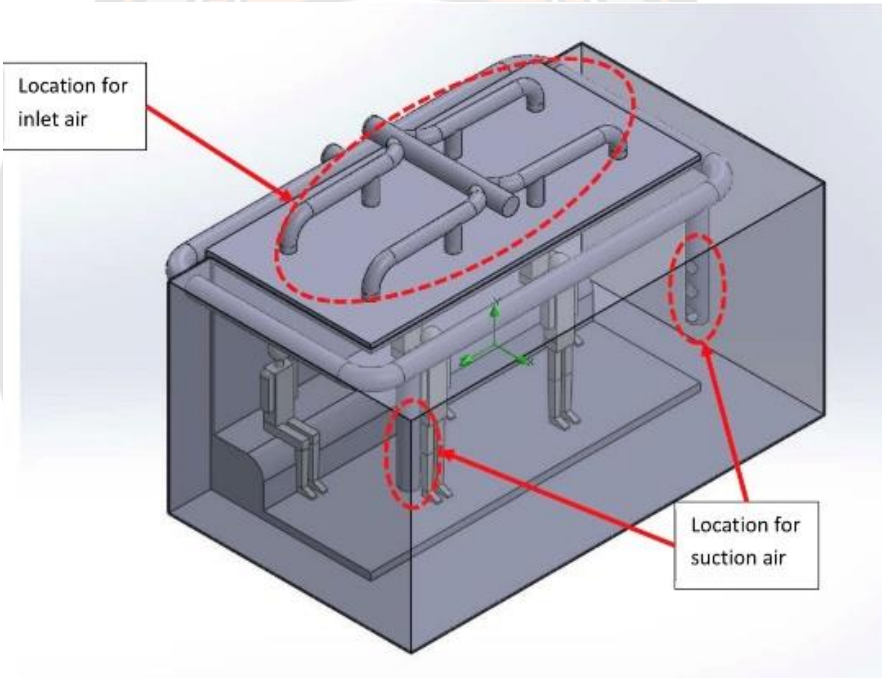


Figure 46 Results after the installation of the hybrid wet scrubber at the bus shelter in April 2023

In addition, the clean air from the purification tower, approximately three to four hundred cubic meters per hour, will be discharged into a clean air curtain, giving the bus shelter an air change rate of more than four, which will create sufficient air circulation, especially on days when there is a lot of dust and when the distribution of pollution will spread less as well from the air stable or not moving as temperature inversion. Figure 46(a) shows passengers in a bus shelter operating with a hybrid wet scrubber. The external air inlet was installed in front of two sides of the bus shelter, and the purified air that entered the shelter's roof is shown in Figure 46(b).

(a)



(b)

Figure 47 a) Passengers waiting inside a bus shelter during the operation of a hybrid wet scrubber and b) Position of suction air and purified air inlet the shelter.

According to the results of the outdoor experiment at the bus shelter, the dust absorbed by the purification tower precipitates as sediment at the bottom of the purification tower. It includes large dust particles, PM 100 as total suspended particulate (TSP), PM 10, and PM 2.5 as shown in Figure 47.

Figure 48 Dust was captured within 60 days in March and April 2023

4.9 The IOT system for controlling the PM 2.5 Hybrid Wet Scrubber

Development of an IoT system for controlling the operation of a PM 2.5 purification tower

1. A PM 2.5 hybrid wet scrubber tower has an 80-90% efficiency and gets the most air volume at the airflow outlet by controlling the increase in water level according to the PM 2.5 concentration at the airflow inlet. If the PM 2.5 sensor at the airflow inlet measuring the PM 2.5 concentration value does not exceed 50 $\mu g/m^3$, the IOT system will control the water level at 50 mm to obtain a volume of clean air of 7 cubic meters per minute. If the PM 2.5 sensor measures the PM 2.5 concentration value ranging from 51-99 $\mu g/m^3$, the system will order the water level to be controlled at 100 mm to obtain a clean air volume of 6 cubic meters per minute. Suppose the PM 2.5 inlet sensor measures the PM 2.5 concentration value of 100 µg/m3 or more; the system will increase the water level and maintain it at 150 mm, resulting in an air output of approximately 5 cubic meters per minute.
2. CO_2 measurements of the IOT system have shown a consistent increase in CO_2 values from 400-440 ppm to 500-550 ppm from 7:00 a.m. to 8:30 a.m. It is a peak traffic hour of the day at the bus stop intersection in front of the hospital. It corresponds to the high PM 2.5 values measured from the airflow inlet of the PM 2.5 hybrid air purification tower.
3. Humidity values affect PM 2.5 sensors. It found that the PM 2.5 measurement in March and April showed high efficiency of PM 2.5 removal up to 90% because it was found that in March and April, Phitsanulok had very high temperature at 35-40 C while having a relative humidity lower than 50%, causing water vapor or tiny water droplets to evaporate into the air mass. Then, the sensors do not detect values from small water particles. Therefore, further study and development must be conducted to improve the PM 2.5 values read by the sensors during periods of high relative humidity.

CHAPTER V

CONCLUSION AND RECOMMENDATION

This study aimed to design a smart wet scrubber tower using an IoT system for real-time monitoring and examine the parameters affecting the PM 2.5 removal efficiency. The following results were obtained from the experiment.

- Increasing the liquid-to-air ratio increased the average PM2.5 removal efficiency. The maximum efficiency (58.6%) was observed at the upper limit of the liquid-to-air ratio of the wet scrubber in the spray section (13.21 l/m^3).
- Spraying with small droplets produced a higher average PM2.5 removal efficiency. A droplet size of 270 µm exhibited the highest efficiency (58.63%).
- Turbulence in the spray wet scrubber tower was applied as a deflector and baffle. Increasingly, the water level in the deflector and baffle enhanced the efficiency. The maximum efficiency (71.56%) was achieved at a water level of 150 mm using only a turbulence system. When operating between water spray and turbulence, the absorption efficiency increases from 71.56% to 87.59% at a 150 mm water level and a 9.03 l/m^3 liquid-to-air ratio.
- The Pall and Raschig ring packing material type did not promote absorption efficiency, as the droplets became larger when packing the material, resulting in a decreased contact area between the surface and water.
- The PM2.5 removal results achieved by the IoT system and hybrid wet scrubber, which are combinations of turbulent and spray wet scrubber technologies, were investigated via experimental methods under indoor and outdoor conditions. Two parameters were analyzed: the ratio of liquid-to-air and the water level above the nozzle. Then, a liquid-to-air of 13.21 l/m^3 and a water level above the nozzle of 150 mm were set up for the

optimum parameters in another similar-sized hybrid wet scrubber tower operating outdoors in the bus shelter. The PM 2.5 concentration at the airflow outlet met the World Health Organization (WHO) and Pollution Control Department of Thailand (PCD) standards throughout the month of operation.

- The wet scrubber tower could clean 13,320 m^3/d of air and remove 2,464 grams of PM2.5 daily.
- This technology can construct a network for building clean air areas so that urban areas can become smart cities [55].

REFERENCES

[1] Clean Air Association of Thailand. (2019). **Clean Air White Paper, Thailand**. Cited Access 7 November 2022 2020; Available from: http://www.tei.or.th/file/library/2019-clean-air-white-paper_26.pdf.

[2] Clean Air Association of Thailand. (2020). **Clean Air Blue Paper, Thailand**. Cited Access 7 November 2020 2020; Available from: https://storage.googleapis.com/planet4-thailand-stateless/2020/08/9f177db4-clean-air-blue-paper.pdf.

[3] Clean Air Association of Thailand. (2022). **Clean Air Green Paper, Thailand**. Cited Access 25 December 2020 2022; Available from: https://thailandcan.org/Clean_Air_Green_Paper_TH.pdf.

[4] Chulalongkorn University. (2020). **Stay Safe in the PM 2.5 Dust**. Cited Access 7 November 2020 2020; Available from: https://www.chula.ac.th/en/news/26593/.

[5] World Health Organization. (2021). **Ambient (outdoor) air pollution**. Cited Access; Available from: https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health.

[6] Oanh, N.T., H. Co, and Y. Kondo. (2009). **Investigation on the Impacts of Urban-Rural Air Pollution on Air Quality and Climate in Southeast Asia**, 2009. Asia-Pacific Network for Global Change Research: The University of Tokyo.

[7] IMD World Competitiveness Center. (2020). **Smart City Index 2020**. Cited Access 14 January 2020 2020; Available from: https://www.imd.org/wcc/world-competitiveness-center-rankings/smart-city-index-2020/.

[8] The UK Foreign Commonwealth and Development Office (FCDO). (2020). **Smart City Handbook: Thailand**. Thailand: Department for International Trade.

[9] Karl B. Schnelle Jr and Charles A. Brown. (2021). **Air Pollution Control Technology Handbook**, ed. s. Edition. CRC Press.

[10] EPA Office of Air Quality Planning and Standards. (1998). **EPA-452/R-97-001, Stationary Source Control Techniques Document for Fine Particulate Matter**. NC: Research Triangle Park.

[11] Kim, H., C. Jung, S.N. Oh, and K.W. Lee. (2001). Particle Removal Efficiency of Gravitational Wet Scrubber Considering Diffusion, Interception, and Impaction. **Environmental Engineering Science**. 18: p. 125-136.

[12] Jiuan, Y.L. (2005). **Evaluation of Wet Scrubber Systems**. Bachelor of Engineering (Mechanical), University of Southern Queensland,

[13] Danzomo, B.A., M. Salami, S. Jabirin, M.R. Khan, and I.M. Nor. (2012). Performance Evaluation of Wet Scrubber System for Industrial Air Pollution Control. **Journal of Engineering and Applied Science**. 7(12): p. 1169-1677.

[14] Mohammad Javad, J., H. Majid, Y. Ahmadreza, M. Yadoolah, G. Roohollah, and K. Marzieh. (2015). The Role of Packing Media in a Scrubber Performance Removing Sulfuric Acid Mists. **International Journal of Occupational Hygiene**. 4(2).

[15] Hegely, L., J. Roesler, P. Alix, D. Rouzineau, and M. Meyer. (2017). Absorption methods for the determination of mass transfer parameters of packing internals: A literature review. **AIChE Journal**. 63(8): p. 3246-3275.

[16] Buonicore, A.J. and W.T. Davis. (1992). **Air Pollution Engineering Manual**. New York: Van Nostrand Reinhold.

[17] Lee, B.-K., B.R. Mohan, S.-H. Byeon, K.-S. Lim, and E.-P. Hong. (2013). Evaluating the performance of a turbulent wet scrubber for scrubbing particulate matter. **Journal of the Air & Waste Management Association**. 63(5): p. 499-506.

[18] Meikap, B.C. and M.N. Biswas. (2004). Fly-ash removal efficiency in a modified multi-stage bubble column scrubber. **Separation and Purification Technology**. 36(3): p. 177-190.

[19] Lee, B.-K., K.-R. Jung, and S.-H. Park. (2008). Development and application of a novel swirl cyclone scrubber—(1) Experimental. **Journal of Aerosol Science**. 39(12): p. 1079-1088.

[20] Park, S.-H. and B.-K. Lee. (2009). Development and application of a novel swirl cyclone scrubber: (2) Theoretical. **Journal of Hazardous Materials**. 164(1): p. 315-321.

[21] Raj Mohan, B. and B.C. Meikap. (2009). Performance characteristics of the particulate removal in a novel spray-cum-bubble column scrubber. **Chemical Engineering Research and Design**. 87(1): p. 109-118.

[22] Wu, X., R.C. Nethery, M.B. Sabath, D. Braun, and F. Dominici. (2020). Air pollution and COVID-19 mortality in the United States: Strengths and limitations of an ecological regression analysis. **Sci Adv**. 6(45).

[23] Kasikorn Research Center. (2020). **Escalating PM 2.5 problem prompts government to speed up measures to address the problem as people pay attention to health**. Cited Access 22 January 2020 2020; Available from: https://www.kasikornresearch.com/en/analysis/k-econ/economy/Pages/z3076.aspx.

[24] Attavanich, W., R. Mungkung, I. Mahathanaseth, S. Sanglestsawai, and A. Jirajari. (2016). **Developing Green GDP Accounting for Thai Agricultural Sector Using the Economic Input Output - Life Cycle Assessment to Assess Green Growth**. in SEE 2016 in conjunction with ICGSI 2016 and CTI 2016 On "Energy & Climate Change: Innovating for a Sustainable Future". Bangkok, Thailand.

[25] Engineering ToolBox. (2008). **Duct Sizing - Equal Friction Method**. Cited Access 1 April 2021 2021; Available from: https://www.engineeringtoolbox.com/equal-friction-method-d_1028.html.

[26] Engineering ToolBox. (2004). **Darcy-Weisbach Pressure and Major Head Loss Equation**. Cited Access 1 April 2021 2021; Available from: https://www.engineeringtoolbox.com/darcy-weisbach-equation-d_646.html.

[27] United States Environmental Protection Agency. (2002). **EPA Air Pollution Control Cost Manual**. Cited Access 7 November 2020 2020; Available from: https://www3.epa.gov/ttncatc1/dir1/c_allchs.pdf.

[28] Mussatti, D. and P. Hemmer. (2002). **EPA/452/B-02-001, Section 6 Particulate Matter Controls, Chapter 2 Wet Scrubbers for Particulate Matter**. Cited Access 3 November 2022; Available from: https://www.epa.gov/sites/default/files/2020-07/documents/cs6ch2.pdf.

[29] Wikipedia. (2022). **Packed bed**. Cited Access; Available from: https://en.wikipedia.org/wiki/Packed_bed.

[30] U.S. Environmental Protection Agency. **Air Pollution Control Technology Fact Sheet (Packed-Bed/Packed-Tower Wet Scrubber)**, in EPA-452/F-03-015.

[31] Susanna Laurén. (2018). **What are surfactants and how do they work?** Cited Access 8 July 2022 2022; Available from: https://www.biolinscientific.com/blog/what-are-surfactants-and-how-do-they-work.
[32] Wang, C., Y. Zhang, K. Dong, B. Wang, S. Li, R. Xin, and Y. Jiang. (2020). Enhanced collection of fine particles in a cyclone using ultrasonic vapor with surfactants. **Advanced Powder Technology**. 31(6): p. 2207-2214.
[33] Danov, K.D., S.D. Kralchevska, P.A. Kralchevsky, K.P. Ananthapadmanabhan, and A. Lips. (2004). Mixed Solutions of Anionic and Zwitterionic Surfactant (Betaine): Surface-Tension Isotherms, Adsorption, and Relaxation Kinetics. **Langmuir**. 20(13): p. 5445-5453.
[34] Li, S., B. Zhao, H. Lin, H. Shuang, X. Kong, and E. Yang. (2021). Review and prospects of surfactant-enhanced spray dust suppression: Mechanisms and effectiveness. **Process Safety and Environmental Protection**. 154: p. 410-424.
[35] Jiang, Y., P. Wang, R. Liu, Y. Pei, and G. Wu. (2020). An Experimental Study on Wetting of Coal Dust by Surfactant Solution. **Advances in Materials Science and Engineering**. 2020: p. 1567461.
[36] Tien, J.C. and J. Kim. (1997). Respirable Coal Dust Control Using Surfactants. **Applied Occupational and Environmental Hygiene**. 12(12): p. 957-963.
[37] Niu, W., W. Nie, M. Yuan, Q. Bao, W. Zhou, J. Yan, F. Yu, C. Liu, N. Sun, and Q. Xue. (2021). Study of the microscopic mechanism of lauryl glucoside wetting coal dust: Environmental pollution prevention and control. **Journal of Hazardous Materials**. 412: p. 125223.
[38] Liang, J., Y. Qian, X. Yuan, L. Leng, G. Zeng, L. Jiang, J. Shao, Y. Luo, X. Ding, Z. Yang, and X. Li. (2018). Span80/Tween80 stabilized bio-oil-in-diesel microemulsion: Formation and combustion. **Renewable Energy**. 126: p. 774-782.
[39] Alfano, B., L. Barretta, A. Del Giudice, S. De Vito, G. Di Francia, E. Esposito, F. Formisano, E. Massera, M.L. Miglietta, and T. Polichetti. (2020). A Review of Low-Cost Particulate Matter Sensors from the Developers' Perspectives. **Sensors**. 20(23): p. 6819.
[40] Hapidin, D.A., C. Saputra, D.S. Maulana, M.M. Munir, and K. Khairurrijal. (2019). Aerosol Chamber Characterization for Commercial Particulate Matter (PM) Sensor Evaluation. **Aerosol and Air Quality Research**. 19(1): p. 181-194.
[41] Hong, G.-H., T.-C. Le, J.-W. Tu, C. Wang, S.-C. Chang, J.-Y. Yu, G.-Y. Lin, S.G. Aggarwal, and C.-J. Tsai. (2021). Long-term evaluation and calibration of three types of low-cost PM2.5 sensors at different air quality monitoring stations. **Journal of Aerosol Science**. 157: p. 105829.
[42] Tubaishat, M. and S. Madria. (2003). Sensor networks: an overview. **IEEE Potentials**. 22(2): p. 20-23.
[43] Noura, M., M. Atiquzzaman, and M. Gaedke. (2019). Interoperability in Internet of Things: Taxonomies and Open Challenges. **Mobile Networks and Applications**. 24(3): p. 796-809.
[44] Rappaport, T.S., R.W. Heath, R.C. Daniels, and J.N. Murdock. (2015). **Millimeter Wave Wireless Communications**. Prentice Hall.
[45] Thantharate, A., C. Beard, and P. Kankariya. (2019). **CoAP and MQTT Based Models to Deliver Software and Security Updates to IoT Devices over the**

Air. in 2019 International Conference on Internet of Things (iThings) and IEEE Green Computing and Communications (GreenCom) and IEEE Cyber, Physical and Social Computing (CPSCom) and IEEE Smart Data (SmartData).
[46] IEEE SA Board of Governors/Corporate Advisory Group (BoG/CAG). (2019). **IEEE Standard for an Architectural Framework for the Internet of Things (IoT)**, 2019 in IEEE Std 2413-2019. p. 1-269.
[47] OMEGA MEASURING INSTRUMENT CO. LTD. (2019). **Recommended Standard no. 232**. Cited Access 30 May 2022 2022; Available from: https://www.omi.co.th/th/article/rs232.
[48] OMEGA MEASURING INSTRUMENT CO. LTD. (2019). **Recommended Standard no. 485**. Cited Access 30 May 2022 2022; Available from: https://www.omi.co.th/th/article/rs485.
[49] Garg, V.K. (2007). **Wireless Communications & Networking**.
[50] Minerva, R., B. Abyi, and R. Domenico. (2015). Towards a definition of the Internet of Things (IoT). **IEEE Internet Initiative**, (1(1)): p. 1-86.
[51] Sethi, P. and S.R. Sarangi. (2017). Internet of Things: Architectures, Protocols, and Applications. **Journal of Electrical and Computer Engineering**. 2017: p. 9324035.
[52] Vogel, B., Y. Dong, B. Emruli, P. Davidsson, and R. Spalazzese. (2020). What Is an Open IoT Platform? Insights from a Systematic Mapping Study. **Future Internet**. 12(4): p. 73.
[53] Quick, D., B. Martini, and R. Choo. (2013). **Cloud Storage Forensics**, ed. 1st. Waltham, MA 02451, USA: Elsevier.
[54] Haswani, N.G. and P.J. Deore. (2018). **Web-Based Realtime Underground Drainage or Sewage Monitoring System Using Wireless Sensor Networks**. in 2018 Fourth International Conference on Computing Communication Control and Automation (ICCUBEA).
[55] Avveduto, A., C. Salisburgo, L. Pace, G. Curci, A. Monaco, M. Giovanni, F. Giammaria, G. Spanto, and P. Tripodi. (2015). **Analysis of a wet scrubber network in the air remediation of industrial workplaces: benefit for the city air quality**, 2015 in Urban Environemntal Pollution 2014.

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APPENDIX

Appendix A PM2.5 Collection Enhancement in a Smart Hybrid Wet Scrubber Tower

processes

MDPI

Article

PM2.5 Collection Enhancement in a Smart Hybrid Wet Scrubber Tower

Akasit Wansom [1], Pisit Maneechot [1], Nattagit Jiteurtragool [2] and Tharapong Vitidsant [3,*]

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Abstract: The removal efficiency of particulate matter of less than 2.5 microns (PM2.5) using an innovative wet scrubber tower with an IoT system for PM2.5 real-time monitoring was investigated. The PM2.5 used in this experiment was obtained from vehicle exhaust, specifically from running the diesel engine of a pickup truck with a range of PM2.5 with a concentration ranging from 50 μg/m^3 to 500 μg/m^3. Focused parameters related to PM2.5 were analyzed, such as the liquid-to-air ratio (it uses air because this device purifies PM2.5 for the airflow from the polluted ambient air), turbulence techniques enabled by the installation of a deflector and a baffle at the airflow inlet, water level fluctuation above the nozzle, spray nozzle size, and the type of packing material. The average PM2.5 removal efficiency was determined for each parameter relevant to the experiment. The results showed that increasing the liquid-to-air ratio increased the average PM2.5 removal efficiency, while the smaller droplet spraying water resulted in higher efficiency. The spray section achieved its highest efficiency at 58.63%, with a liquid-to-air ratio of 13.21 L/m^3 and droplet size of 270 μm. The turbulence technique showed a higher potential for the removal of PM2.5, with an efficiency level of 71.56% at a water level of 150 mm. Moreover, the operation incorporates water spraying and turbulence induction, promoting higher removal efficiency, from 71.56% to 87.59%, at a water level of 150 mm and a liquid-to-air ratio of 9.03 L/m^3. This condition resulted in an output concentration of PM2.5 less than 15 μg/m^3, which meets the WHO's guidelines for PM2.5 intensity. This cleverly designed wet scrubber tower can clean up to 13,320 m^3 of air daily or remove up to 2,464 g of PM2.5 per day. No enhancement of PM2.5 removal efficiency was observed when two types of packing materials were used due to the formation of bigger droplets as the packing materials were passed through.

Keywords: hybrid; IoT system; wet scrubber; PM2.5; removal efficiency; turbulence

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Citation: Wansom, A.; Maneechot, P.; Jiteurtragool, N.; Vitidsant, T. PM2.5 Collection Enhancement in a Smart Hybrid Wet Scrubber Tower. *Processes* **2023**, *11*, 3306. https://doi.org/10.3390/pr11123306

Academic Editor: Yo-Ping Huang

Received: 6 November 2023
Revised: 23 November 2023
Accepted: 24 November 2023
Published: 27 November 2023

1. Introduction

Particulate matter 2.5 (PM2.5) is one of the eight most common air pollutants known as criteria air pollutants. This list includes carbon monoxide (CO), lead (Pb), ground-level ozone (O_3), nitrogen dioxide (NO_2), ammonia (NH_3), sulfur dioxide (SO_2), particulate matter 10 (PM10), and particulate matter 2.5 (PM2.5) [1]. PM2.5 is one of the biggest air pollution problems threatening human health, the environment, and the economy worldwide. The World Health Organization (WHO) announced that, in 2016, outdoor air pollution led to the death of 4.2 million people, with 91% of these people living in Asian countries and the West Pacific [2]. In Bangkok, PM2.5 originates from vehicle emissions in transportation and biomass combustion. In the dry season, which occurs between January and April every year, 45% of the PM2.5 pollution in Bangkok comes from diesel-powered vehicles, with the highest value of PM2.5 not exceeding 300 μm/m^3 [3].

There are many end-of-pipe technologies to eliminate and reduce the levels of PM2.5 in air pollutants, such as cyclones, scrubbers, electrostatic precipitators, and baghouse filters. The effectiveness of each of these techniques depends on how the device is designed and applied. For instance, a cyclone can filter dirty air with 90% efficiency and can filter dust with a diameter greater than 20 μm. The removal efficiency of a spray tower can reach 90% for particles with a diameter exceeding 5 μm, and it typically falls within the range of 60% to 80% for particles with diameters ranging from 3 μm to 5 μm. When particles have a diameter of less than 3 μm, the removal efficiency of a spray tower decreases to below 50%. The venturi scrubber boasts a removal efficiency of 98% and can effectively filter particles as small as 0.5 μm in diameter. The electrostatic precipitator has a dirty-air-filtering efficiency of 99%. It can filter dust that is 1 μm in diameter but consumes substantial amounts of power. The baghouse dirty-air-filtering efficiency is nearly 100%. It can filter dust that is 1 μm in diameter; however, this device has high levels of airflow resistance and is expensive to operate and maintain [4,5].

Kim et al. [6] conducted a theoretical analysis of a gravitational wet scrubber particle removal efficiency that considered impaction, interception, and diffusion. Impaction generally removes dust with a diameter over 1 μm; the Brownian diffusion mechanism can remove particles smaller than 0.1 μm in diameter. Jiuan [7] also maintains that a counter-current flow arrangement is more efficient than a crossflow arrangement. Thus, particles are conditioned during scrubbing by wetting, trapping in water blankets, and impacting them with water droplets. To enhance the efficiency of the wet scrubber, numerous factors influencing the scrubbing process need to be taken into account, including scrubber design, droplet size, sizing, packed bed material, packed bed depth, selection of scrubbing liquid, and distribution rate of washing liquid [8]. In this study, we examined the improvement of the counterflow spray wet scrubber and its PM2.5 removal efficiency by reviewing and experimenting with three techniques. Three variables are relevant to PM removal efficiency enhancement: (1) droplet size (for a wet spray scrubber), (2) packed bed, and (3) turbulence in the wet scrubber. Smaller droplets can capture finer particles because they have a larger surface area-to-volume ratio. However, if the droplet size is too small, the momentum of the pollutant airflow can be imparted to the droplets. Decreasing the relative velocity between the droplet and particles results in lower collection efficiency [4]. The purpose of a packed bed is to increase the area of contact between two or three phases in a scrubbing process, such as liquid and gas [9]. The height and type of packing can be changed to improve the mass transfer. A larger packed bed depth is preferred for a scrubber since it helps boost absorption and efficiency [10]. Many packing types, such as the Pall ring, Raschig ring, Tri-packs, Tellerette, Berl saddle, Intalox, and others, are made from various materials [11]. The U.S. EPA suggests that packed-bed scrubbers are more suitable for gas scrubbing than PM scrubbing, as clogs in the bed and plugging make it more difficult to access, clean, and change the spray heads. The packed-bed wet scrubber can be used for low dust-loading applications and particulate matter larger than 5 μm. A deflector and baffle create water turbulence, allowing polluted air to flow through fluctuating water. This method can simultaneously increase the wettability of particles, agglomerate, and remove dust [12]. Meikap et al. [13] achieved a removal efficiency of 95% to 99% for particulate matter sizes of 0.1–100 μm in a modified multi-stage bubble column scrubber. Lee et al. [14] found that a swirling cyclone wet scrubber could collect 2.5 μm particles with an efficiency of 86% and 5 μm particles with an efficiency of 97%. Park et al. [15] observed that wet scrubbing with polydisperse aerosol can remove more than 90% of particles larger than 2 μm. Mohan [16] reported 75–99% PM2.5 removal efficiency with a novel spray-bubbler scrubber in which the bubble column removed maximum particles when the concentration increased. Park [15] investigated the performance of a water turbulence scrubber for the removal of particle matter and found that particles more prominent than 1 μm were drawn efficiently (nearly 100%), depending on the flow rate, dust-laden air stream concentration, and the reservoir water level. Hence, spray columns and bubble column scrubbers are efficient in scrubbing particulate matter from effluent [12]. The objectives of this research were to determine the effect of each parameter and combination of them on PM2.5 removal efficiency, design an actual size wet scrubber in the bus shelter for the protection of pedestrians from roadside traffic pollution, and monitor the real-time PM2.5 concentration with an IoT system to calculate the accurate removal quantity of PM 2.5.

2. Building and Developing a Prototype PM2.5 Absorption Tower

Due to the lack of theories for the design of an absorber tower to eliminate PM2.5, the design of the absorption tower relied on the design of the dissolved gas evaporator as a guideline. Jiuan [7] examined the structure and efficiency of counterflow and crossflow wet scrubbers and found that counterflow has a higher efficiency than crossflow. Therefore, we built the absorption tower prototype based on a counterflow wet scrubber with an air blower of 1 hp 220 V 50 Hz and a 1 hp 220 V 50 H water pump. The selected air blower could provide an airflow of up to 12.5 m^3/min with an inverter frequency adjustment. The chosen water pump could provide a water flow of 45 L/min; thus, the experimental wet scrubber tower could achieve a liquid-to-air ratio of up to 13.21 L/m^3. The wet scrubber parameters and features are presented in Table 1 and Figure 1, respectively.

Table 1. Summary of the spray wet scrubber design parameters.

Parameter	Numerical Value
Tower height	4 m
Tower width (square)	0.85 m
Transfer unit height	2 m
Spray head	12 pcs
Inlet diameter	100 mm
Outlet diameter	150 mm
Liquid-to-air ratio (up to airflow rate)	up to 13.21 L/m^3
Blower with inverter for frequency adjustment	1 hp
Water pump	1 hp
Water tank	390 L

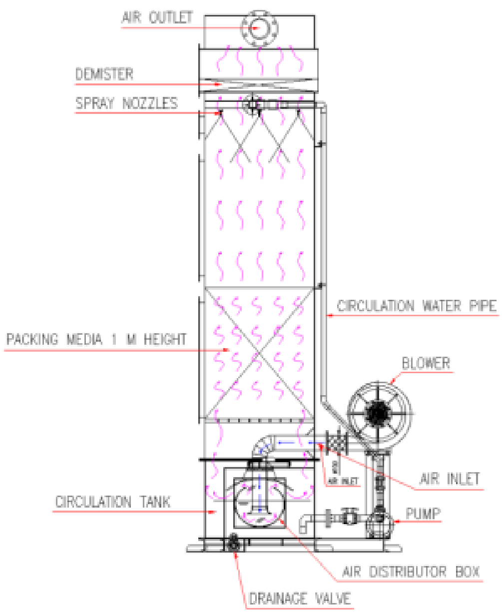


Figure 1. Wet scrubber design.

3. Integrating the IoT System for the Hybrid Wet Scrubber

The Internet of Things (IoT) refers to devices, objects, or machines with IoT controllers, software, sensors, and network connections [17,18]. These devices can store and exchange data over wireless communication on the Internet. The data can be anything from environmental data collected through sensors or signals used for the remote control of the IoT device. The proposed IoT system was incorporated into the tower to manage the behavior data of the proposed hybrid wet scrubber tower for performance analysis. Figure 2 illustrates the detailed architecture of the designed IoT system.

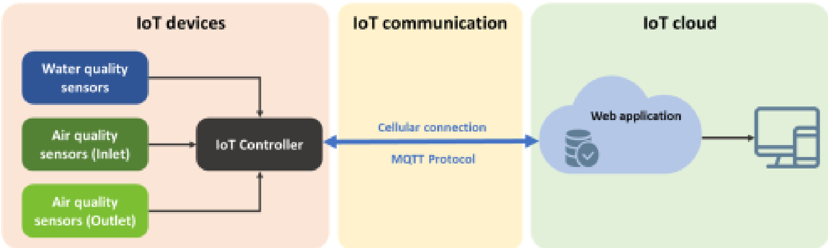


Figure 2. The architecture of the IoT system incorporated into the proposed hybrid wet scrubber tower.

The proposed system consisted of three layers: (1) IoT devices incorporated into the wet scrubber tower, (2) IoT communication, such as protocol and network technology, and (3) IoT cloud, which is a web application service for data collection and monitoring [19,20]. The IoT devices layer contains numerous sensors connected to the wet scrubber tower that are required for data collection [21,22]. In the water tank of the wet scrubber tower, water quality sensors were installed to collect data such as water level, pH, and electrical conductivity (EC) of water. At the inlet and outlet of the wet scrubber tower, air quality data, such as PM2.5 (μg/m^3), relative humidity level (%), and temperature (°C), were collected. Subsequently, all the data collected from sensors were processed and transmitted to the IoT cloud layer using an IoT controller, which is an industrial-grade PLC controller. The IoT communication layer refers to the communication process between IoT devices and the IoT cloud. The IoT controller in the IoT devices layer was designed to connect and send all the data over cellular networks. Therefore, the MQTT protocol was essential in establishing communication between the IoT controller and the cloud [23]. All data collected from the IoT devices layer connected to the wet scrubber tower were processed in the cloud layer of the IoT system. The IoT cloud layer comprises a database and web application server to store the data and wait for the user to request the data display on the web browser [24].

4. Experimental Procedure

The experimental setup for PM2.5 removal by the IoT system and hybrid wet scrubber, using a combination of turbulent and spray wet scrubber technology, was developed as follows.

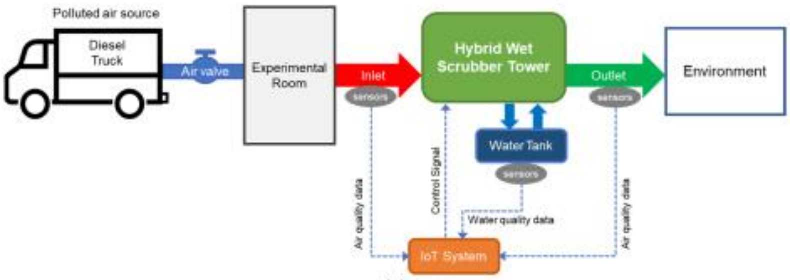
(1) A 60 m^3 experimental room was built as a controlled environment. Polluted air was produced using 2500 cc diesel direct engines from a 10-year-old pickup truck.

(2) The prototype consisted of the experimental absorption tower encompassing an IoT system for real-time monitoring and was installed at the wet scrubber tower air inlet and outlet to measure PM2.5 levels. The Honeywell HPMA115S0 sensor was selected for this experiment. This suitable sensor is based on the EPA standards [25,26]. The HPMA115S0 sensor is a laser-based sensor that uses the light scattering method to measure the concentration of particles in the range of 0–1000 μg/m^3. The sensor can provide an accuracy of ±15 μg/m^3 for the measurement range of 0–1000 μg/m^3 in control environments with a temperature of 25 °C and humidity of less than 95%.

(3) PM2.5 concentrations in the inlet and outlet were measured using real-time monitoring over 4 h per experiment. According to (3), the PM 2.5 dust concentration at the inlet of every investigation was adjusted from 0 to 500 $\mu g/m^3$. The dust removal efficiency was obtained using the following formula:

$$\eta_{PM2.5} = \frac{M_{PM2.5,i} - M_{PM2.5,o}}{M_{PM2.5,i}} \times 100\% \quad (1)$$

where $M_{PM2.5,i}$, $M_{PM2.5,o}$, and $\eta_{PM2.5}$ were computed with 15 min intervals of data from the sensor monitor. $M_{PM2.5,i}$ and $M_{PM2.5,o}$ represent the concentration of PM2.5 in the inlet and outlet streams, respectively, and the area under the curve of PM2.5 concentration with interval time. The experimental setup is presented in Figure 3.



(**a**)

(**b**)

Figure 3. (**a**) Diagram of the wet scrubber tower with an IoT system for an indoor experiment; (**b**) developed wet scrubber tower installed indoors.

5. Result and Discussion

In experiment (3), the data on PM2.5 were collected from a bus shelter near the road in the center of the Phitsanulok municipality during the dry season between January and April 2023. The result was that the highest PM2.5 concentration occurred in February (223 $\mu g/m^3$) (See Figure 4).

The parameters for PM2.5 removal by wet scrubber tower, such as liquid-to-air ratio, turbulence created by water level above the nozzle, water droplet size, and packing material, were examined.

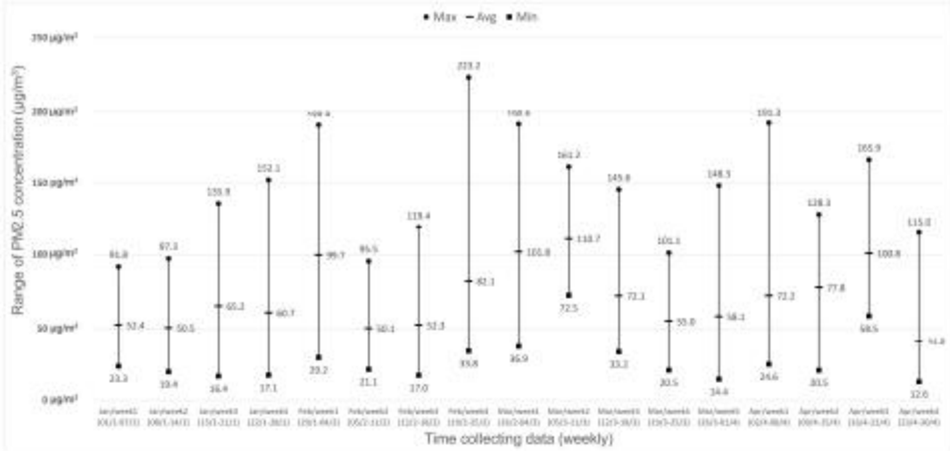


Figure 4. PM2.5 data were collected from a bus shelter near the road in the center of the Phitsanulok municipality between January and April 2023.

5.1. *Effect of Liquid-to-Air Ratio*

We investigated PM2.5 removal efficiency while keeping the flow rate of spray water constant at 45 L/min, using water droplets with a size of 270 µm. The airflow rate inputs were 8.51 m^3, 6.08 m^3, and 3.40 m^3. The L/G coefficient, giving values of 5.41 L/m^3, 9.56 L/m^3, and 13.21 L/m^3, is calculated from the water for the spray part at 45 L/min divided by the air volume that decreases by the air velocity falling from water resistance increasing by the water level above the nozzle. The influence of the liquid-to-air ratio on the average efficiency of PM2.5 removal with an air inlet concentration of 50–500 µg/m^3 is shown in Figure 5, and the average efficiency of removal of PM2.5 is presented in Table 2. The results demonstrate that the average efficiency in removing PM2.5 operated using only the spray scrubbing method was 38.6% at the liquid-to-air ratio of 5.14 L/m^3. However, the average efficiency increased, reaching 58.6% at the liquid-to-air ratio of 13.21 L/m^3. Thus, lowering the air flow rate (lower amount of PM2.5) captured more PM2.5 water capacity (still constant flow rate at 45 L/min). The increasing liquid-to-air ratio resulted in a higher efficiency, which Danzomo [8] also reported. The experiment outcomes align with those recommended by the US EPA, with removal efficiencies of 60–80% for particles with a diameter ranging from 3 µm to 5 µm. Below 3 µm, removal efficiencies declined to less than 50% for the spray scrubbing method [4,5].

Table 2. Effect of liquid-to-air ratio as 5.41 L/m^3 and 13.21 L/m^3 on PM2.5 removal efficiency.

Liquid-to-Air Ratio L/m^3	Average Efficiency with Spray %
5.14	38.60
9.56	49.86
13.21	58.60

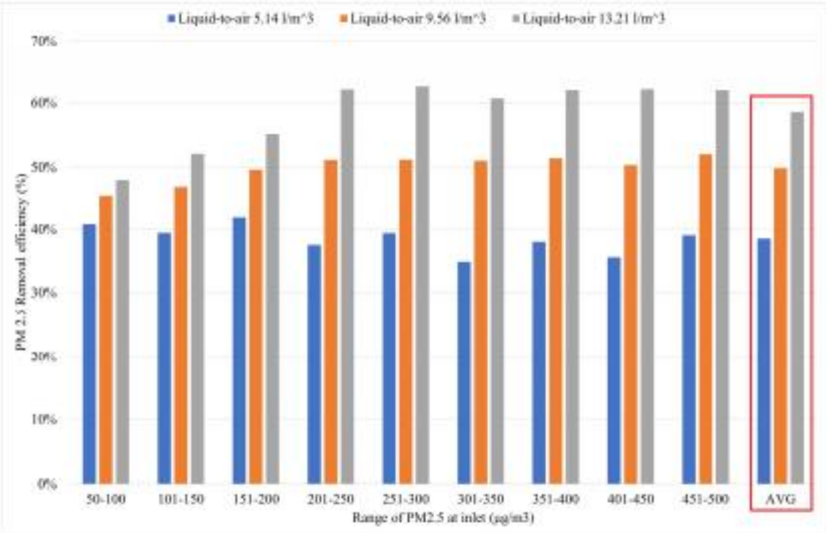


Figure 5. Effect of liquid-to-air ratio as 5.41 L/m^3, 9.56 L/m^3, and 13.21 L/m^3 on PM2.5 removal: average efficiency with a water droplet size of 270 µm operating with an air inlet concentration range of 50–500 µg/m^3.

5.2. Effect of Water Droplet Size

The effect of water droplet size on the average PM2.5 removal efficiency was investigated using a liquid-to-air ratio of 13.21 L/m^3. The results are presented in Table 3. Water droplets with a size of 270 µm, 380 µm, and 520 µm had an average PM2.5 removal efficiency of 58.63%, 53.03%, and 38.63%, respectively. Small water droplets enhanced PM2.5 absorption more than larger ones, generating more surface contact area and greater absorption capacity. This was in line with the results presented by Mussatti [27], who found that smaller droplets captured finer particles, as they had a larger surface-area-to-volume ratio [4].

Table 3. The average efficiency of PM2.5 removal is based on water droplet size.

Mean Droplet Diameter (µm)	PM2.5 Removal Efficiency (%)					Avg. (%)
	0–100	101–200	201–300	301–400	401–500	
270	65.2	61.12	60.03	55.15	51.65	58.63
380	58.96	55.14	51.05	49.89	50.1	53.03
520	45.12	40.16	39.43	35.31	33.11	38.63

5.3. Effect of Turbulence

The turbulence in this spray wet scrubber tower was achieved by installing a deflector and baffle (Figure 6) at the airflow inlet. Moreover, the water level above the nozzle was varied (50, 100, or 150 mm) by keeping the spray water at 45 L/min. This experiment used turbulence coupled with spraying water droplets, and PM2.5 absorption was expected at droplets and deflectors.

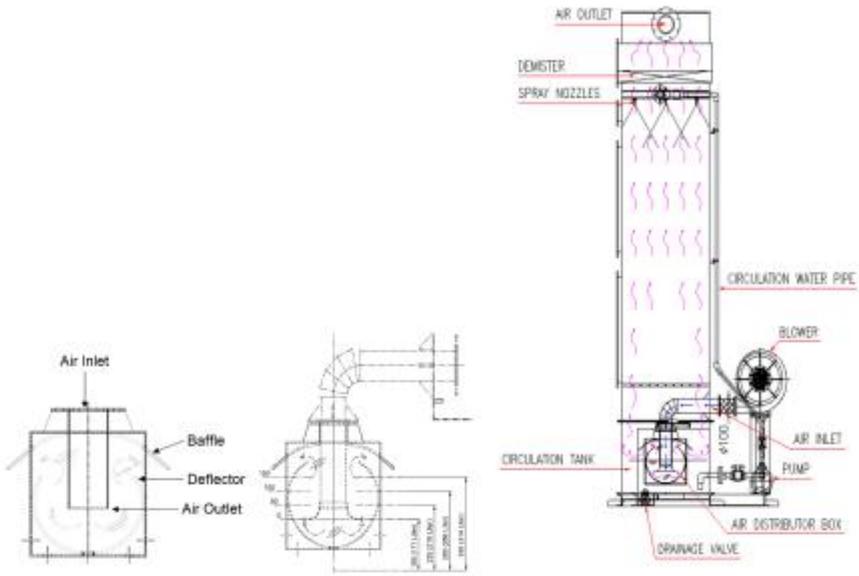


Figure 6. A schematic diagram of the turbulence wet scrubber system.

The deflector and baffle reduced airflow velocity by water airflow resistance and increased the efficiency of PM 2.5 removal. The results of the average efficiency of PM2.5 removal as a function of inlet PM2.5 concentration in the range of 50–500 $\mu g/m^3$ and different water levels above the nozzle, comparing with and without the spraying water, are presented in Table 4 and Figure 7. During operation, a pressure drop was observed from 155.45 mm H_2O to 223.25 mm H_2O with a 0–150 mm water level. This pressure drop was created by airflow resistance. Using only turbulence without water spraying had an average efficiency of 42.83%, 59.67%, 66.03, and 71.56.59% at 0 mm, 50 mm, 100 mm, and 150 mm of water above the air outlet, respectively. This could be explained by the fact that higher water above the air outlet caused a longer residence time of absorption, resulting in higher PM2.5 removal.

Table 4. Increasing liquid-to-air ratio as a function of water level above the nozzle.

Water Level (mm)	Liquid-to-Air Ratio (L/m^3)	Pressure Drops (mm H_2O)	Average Efficiency: Only Turbulence (%)	Average Efficiency: Turbulence with Water Spraying (%)
0	5.14	155.45	42.83	48.55
50	6.38	175.97	59.67	71.12
100	7.26	204.99	66.03	80.83
150	9.03	223.25	71.56	87.59

In contrast, using turbulence with water spraying produced an average efficiency of 48.55%, 71.12%, 80.83%, and 87.59% at 0 mm, 50 mm, 100 mm, and 150 mm of water above the air outlet, respectively. Adding water spraying absorption to the turbulence technique enhanced PM2.5 removal efficiency. In particular, higher water levels created a higher difference in average efficiency between turbulence and turbulence coupled with water spraying, which was 16% at a water level of 150 mm. The airflow speed was reduced by the airflow resistance of water above the air outlet, creating a higher liquid-to-air ratio from 5.14 L/m^3 to 9.03 L/m^3. Therefore, increased PM2.5 removal efficiency was observed with rising water levels, as shown in Table 4. This result was observed in previous studies [12,13,15,16]. Moreover, the results of the concentration of PM2.5 output during operation of the water spraying system with turbulence at water levels of 50–150 mm was less than 15 μg/m^3, which met WHO guidelines for PM2.5 intensity.

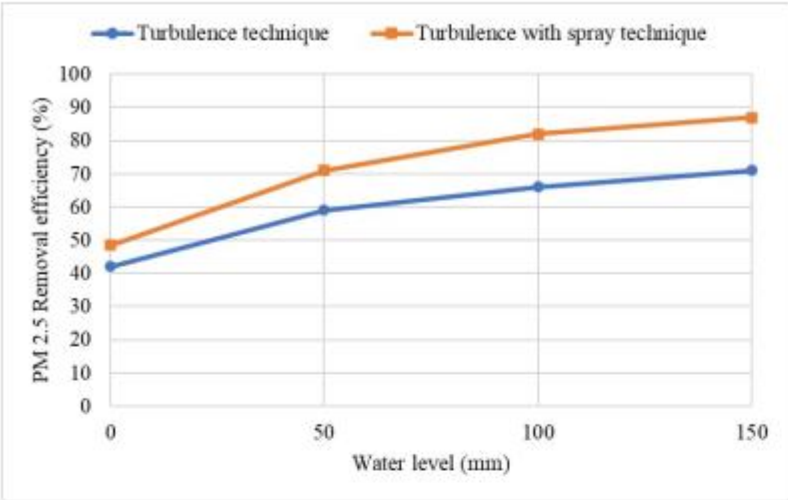


Figure 7. Comparison of PM2.5 removal efficiency for only turbulence and turbulence with water spraying.

Figure 8 shows the PM2.5 removal using turbulence with a water level of 150 mm operating with water spraying, the method which produced the highest efficiency. Figure 8 also presents the average removal efficiency and PM2.5 outlet concentration at an inlet range of 50–500 μg/m^3. The average efficiency remained in the 85–92% range, whereas the outlet concentration increased from 9.88 μg/m^3 to 14.62 μg/m^3, and the inlet concentration increased from 50 μg/m^3 to 250 μg/m^3. The outlet concentration found in this study (14.62 μg/m^3) was slightly lower than the WHO standard, as this standard specifies a PM2.5 outlet concentration of less than 15 μg/m^3 at an inlet concentration of 250 μg/m^3. However, the average outlet concentration over the range inlet concentration of 50–500 μg/m^3 was 31.66 μg/m^3. This met the guidelines of the Pollution Control Department of Thailand, which allows outlet concentrations of less than 35 μg/m^3.

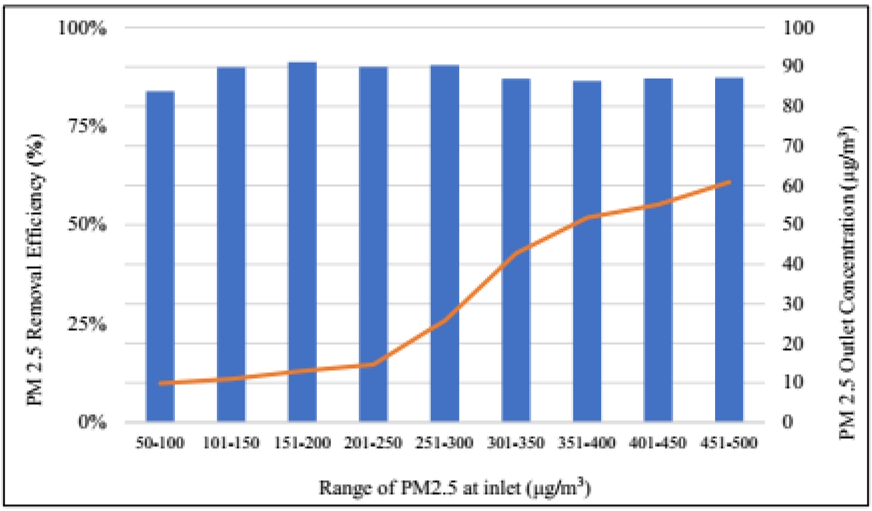


Figure 8. Effect of 150 mm water level on average PM2.5 removal efficiency and PM2.5 outlet concentration operating with water spraying.

5.4. Effect of Packed Bed Type Absorption Tower

The packing material was expected to promote PM2.5 absorption due to increased contact surface and time between air and water. We used two types of packing materials: the Pall ring (A), with a specific surface of 102 m^2/m^3 of media, and the Raschig ring (B), with 190 m^2/m^3 of media (Figure 9). Each type was filled in an absorption tower with approximately the same surface contacting area of 100 m^2. The effect of two types of packing material on the average PM2.5 removal was investigated in relation to the average PM2.5 removal in the absence of packing material. During operation, the liquid-to-air ratio and water droplet size were 13.21 L/m^3 and 270 µm, respectively. They were set up with an air input concentration range of 50–500 $\mu g/m^3$. Figure 10 and Table 5 show the results of the experiments with and without packing material. The average PM2.5 removal efficiency with water spraying only, water spraying and packed bed type A, and water spraying, and packed bed type B was 58.63%, 53.03%, and 52.31%, respectively. No improvement was found after adding packing material. The efficiency of using both types of packing material was approximately the same and it was lower than that obtained without any packing material by approximately 5%. The function of both types of packing material was the deceleration of the droplets with barriers in packing material and droplets merged to form bigger droplets when hitting the barriers, resulting in a decrease in contact surface area between air and water. US EPA [5] suggests that packed-bed scrubbers are more suitable for gas scrubbing than PM scrubbing, as the bed clogs and plugging are more challenging to access and clean and it is challenging to change the spray heads. The packed-bed wet scrubber can be used for low dust-loading applications and particulate matter larger than 5 µm [4,5].


(a) (b)

Figure 9. Packed bed type. (a) Pall ring; (b) Raschig ring.

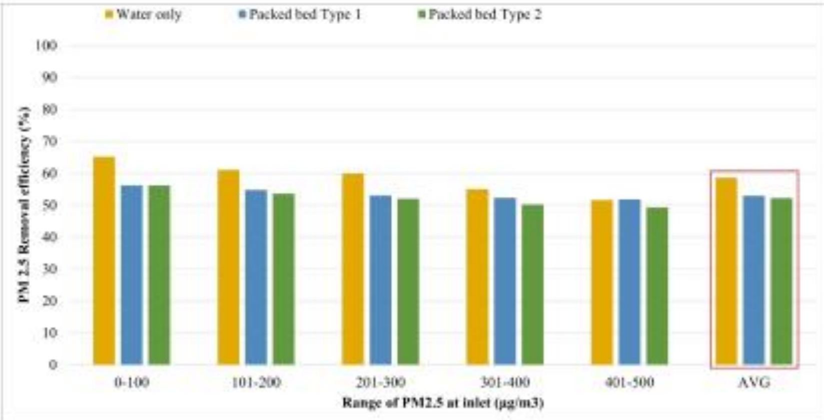


Figure 10. Effect of packed bed on average efficiency of PM2.5 removal.

Table 5. Effect of packed bed type.

Experiment Condition	PM2.5 Removal Efficiency (%)					Avg. (%)
	0–100	101–200	201–300	301–400	401–500	
Spraying water only	65.2	61.12	60.03	55.15	51.65	58.63
Spraying water and packed bed type A	56.25	54.82	53.08	52.36	51.85	53.03
Spraying water and packed bed type B	56.19	53.66	52.12	50.26	49.33	52.31

6. Conclusions

This study aimed to design a smart wet scrubber tower using the IoT system for real-time monitoring and examine the parameters that affected the performance of PM2.5 removal efficiency. The following results were obtained:

- Increasing the liquid-to-air ratio increased the average PM2.5 removal efficiency. The maximum efficiency (58.6%) was observed at the upper limit of the liquid-to-air ratio of the wet scrubber (13.21 L/m^3).

- Spraying with small droplets produced a higher average PM2.5 removal efficiency. A droplet size of 270 μm exhibited the highest efficiency (58.63%).
- Turbulence in the spray wet scrubber tower was enabled via installation of a deflector and baffle. Increasingly, the water level in the deflector and baffle enhanced efficiency. The maximum efficiency (71.56%) was achieved at a water level of 150 mm using only a turbulence system. When the wet scrubber tower operates using both spraying water and turbulence, absorption efficiency increases from 71.56% to 87.59% at 150 mm of water level and 9.03 L/m^3 liquid-to-air ratio. This condition produced an output concentration of PM2.5 that met the WHO guidelines for PM2.5 intensity. The wet scrubber tower could clean 13,320 m^3/d of air and remove 2464 g of PM2.5 daily.
- The Pall and Raschig rings packing material type did not promote absorption efficiency, as the droplets became bigger when passing through the packing the material, resulting in a decreasing contact area between the surface and water.

Author Contributions: Conceptualization, A.W.; Methodology, A.W.; Software, A.W. and N.J.; Validation, P.M. and T.V.; Formal analysis, A.W. and T.V.; Investigation, A.W. and P.M.; Resources, A.W.; Data curation, A.W. and N.J.; Writing—original draft, A.W.; Writing—review & editing, T.V.; Supervision, T.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Broadcasting and Telecommunications Research and Development Fund for Public Interest Thailand/Granted No. A64-1-(2)-005.

Data Availability Statement: Data are available on request from the authors.

Acknowledgments: The authors would like to express gratitude to the Center of Fuels and Energy from Biomass, Chulalongkorn University, for their kind support throughout this research project.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Chulalongkorn University. Stay Safe in the PM 2.5 Dust. Available online: https://www.chula.ac.th/en/news/26593/ (accessed on 7 November 2020).
2. Clean Air Association of Thailand. Clean Air White Paper, Thailand. Available online: http://www.tei.or.th/file/library/2019-clean-air-white-paper_26.pdf (accessed on 7 November 2022).
3. Oanh, N.T.; Kondo, Y.; Co, H.X. *Investigation on the Impacts of Urban-Rural Air Pollution on Air Quality and Climate in Southeast Asia*; Final report for APN project: ARCP2007-07CMY-Oanh; Asia Pacific Network for Global Change Research: Kobe, Japan, 2009.
4. Karl, B.S., Jr.; Charles, A.B. *Air Pollution Control Technology Handbook*; CRC Press: Boca Raton, FL, USA, 2021.
5. United States Environmental Protection Agency. EPA Air Pollution Control Cost Manual. Available online: https://www3.epa.gov/ttncatc1/dir1/c_allchs.pdf (accessed on 7 November 2020).
6. Kim, H.; Jung, C.; Oh, S.N.; Lee, K.W. Particle Removal Efficiency of Gravitational Wet Scrubber Considering Diffusion, Interception, and Impaction. *Environ. Eng. Sci.* **2001**, *18*, 125–136. [CrossRef]
7. Jiuan, Y.L. *Evaluation of Wet Scrubber Systems*; University of Southern Queensland: Toowoomba, QLD, Australia, 2005.
8. Danzomo, B.A.; Salami, M.J.E.; Jabirin, S.; Khan, M.; Nor, I.M. Performance Evaluation of Wet Scrubber System For Industrial Air Pollution Control. *ARPN J. Eng. Appl. Sci.* **2012**, *7*, 1669–1677.
9. Mohammad Javad, J.; Majid, H.; Ahmadreza, Y.; Yadoolah, M.; Roohollah, G.; Marzieh, K. The Role of Packing Media in a Scrubber Performance Removing Sulfuric Acid Mists. *Int. J. Occup. Hyg.* **2015**, *4*, 26–31.
10. Hegely, L.; Roesler, J.; Alix, P.; Rouzineau, D.; Meyer, M. Absorption methods for the determination of mass transfer parameters of packing internals: A literature review. *AIChE J.* **2017**, *63*, 3246–3275. [CrossRef]
11. Buonicore, A.J.; Davis, W.T. *Air Pollution Engineering Manual*; Van Nostrand Reinhold: New York, NY, USA, 1992.
12. Lee, B.-K.; Mohan, B.R.; Byeon, S.-H.; Lim, K.-S.; Hong, E.-P. Evaluating the performance of a turbulent wet scrubber for scrubbing particulate matter. *J. Air Waste Manag. Assoc.* **2013**, *63*, 499–506. [CrossRef] [PubMed]
13. Meikap, B.C.; Biswas, M.N. Fly-ash removal efficiency in a modified multi-stage bubble column scrubber. *Sep. Purif. Technol.* **2004**, *36*, 177–190. [CrossRef]
14. Lee, B.-K.; Jung, K.-R.; Park, S.-H. Development and application of a novel swirl cyclone scrubber—(1) Experimental. *J. Aerosol Sci.* **2008**, *39*, 1079–1088. [CrossRef]
15. Park, S.-H.; Lee, B.-K. Development and application of a novel swirl cyclone scrubber: (2) Theoretical. *J. Hazard. Mater.* **2009**, *164*, 315–321. [CrossRef] [PubMed]
16. Raj Mohan, B.; Meikap, B.C. Performance characteristics of the particulate removal in a novel spray-cum-bubble column scrubber. *Chem. Eng. Res. Des.* **2009**, *87*, 109–118. [CrossRef]

17. Noura, M.; Atiquzzaman, M.; Gaedke, M. Interoperability in Internet of Things: Taxonomies and Open Challenges. *Mob. Netw. Appl.* **2019**, *24*, 796–809. [CrossRef]
18. Sethi, P.; Sarangi, S.R. Internet of Things: Architectures, Protocols, and Applications. *J. Electr. Comput. Eng.* **2017**, *2017*, 9324035. [CrossRef]
19. Minerva, R.; Abyi, B.; Domenico, R. Towards a definition of the Internet of Things (IoT). *IEEE Internet Initiat.* **2015**, *1*, 1–86.
20. *IEEE Std 2413–2019*; IEEE Standard for an Architectural Framework for the Internet of Things (IoT). IEEE: New York, NY, USA, 2020; pp. 1–269. [CrossRef]
21. Cao, K.; Liu, Y.; Meng, G.; Sun, Q. An Overview on Edge Computing Research. *IEEE Access* **2020**, *8*, 85714–85728. [CrossRef]
22. Tubaishat, M.; Madria, S. Sensor networks: An overview. *IEEE Potentials* **2003**, *22*, 20–23. [CrossRef]
23. Hunkeler, U.; Truong, H.L.; Stanford-Clark, A. MQTT-S—A publish/subscribe protocol for Wireless Sensor Networks. In Proceedings of the 2008 3rd International Conference on Communication Systems Software and Middleware and Workshops (COMSWARE '08), Bangalore, India, 6–10 January 2008; pp. 791–798.
24. Paolis, L.T.D.; Luca, V.D.; Paiano, R. Sensor data collection and analytics with thingsboard and spark streaming. In Proceedings of the 2018 IEEE Workshop on Environmental, Energy, and Structural Monitoring Systems (EESMS), Salerno, Italy, 21–22 June 2018; pp. 1–6.
25. Alfano, B.; Barretta, L.; Del Giudice, A.; De Vito, S.; Di Francia, G.; Esposito, E.; Formisano, F.; Massera, E.; Miglietta, M.L.; Polichetti, T. A Review of Low-Cost Particulate Matter Sensors from the Developers' Perspectives. *Sensors* **2020**, *20*, 6819. [CrossRef] [PubMed]
26. Hong, G.-H.; Le, T.-C.; Tu, J.-W.; Wang, C.; Chang, S.-C.; Yu, J.-Y.; Lin, G.-Y.; Aggarwal, S.G.; Tsai, C.-J. Long-term evaluation and calibration of three types of low-cost PM2.5 sensors at different air quality monitoring stations. *J. Aerosol Sci.* **2021**, *157*, 105829. [CrossRef]
27. Mussatti, D.; Hemmer, P. EPA/452/B-02-001, Section 6 Particulate Matter Controls, Chapter 2 Wet Scrubbers for Particulate Matter. Available online: https://www.epa.gov/sites/default/files/2020-07/documents/cs6ch2.pdf (accessed on 3 November 2022).

Appendix B PM2.5 Removal in Bus Shelter in Phitsanulok Province by Wet Scrubber with IoT System

การกำจัดฝุ่น 2.5 ไมครอนในที่พักรถโดยสารจังหวัดพิษณุโลก ด้วยหอบำบัดแบบเปียกด้วยระบบน้ำแบบผสมผสานพร้อมระบบอินเทอร์เน็ตของสรรพสิ่ง

PM2.5 Removal in Bus Shelter in Phitsanulok Province by Wet Scrubber with IoT System

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บทคัดย่อ

งานวิจัยนี้มีความมุ่งหมายที่จะปรับปรุงคุณภาพอากาศภายในที่พักผู้โดยสารรถประจำทางบริเวณริมถนนเพื่อป้องกันฝุ่นขนาด 2.5 ไมครอน โดยเสนอการพัฒนาระบบอินเทอร์เน็ตของสรรพสิ่ง (IoT) ติดตั้งกับหอบำบัดแบบเปียกที่ผสมผสานของระบบปั่นป่วนของน้ำ-อากาศเพื่อวัดประสิทธิภาพการกำจัดฝุ่นแบบตามเวลาจริง(real time)งานวิจัยนี้แบ่งเป็น 2 ส่วน คือการทดลองโดยใช้หอบำบัดอากาศแบบเปียกขนาดเดียวกันภายใต้การจำลองในห้องปฏิบัติการ และในพื้นที่จริงบริเวณที่พักผู้โดยสารรถประจำทาง โดยตัวแปรที่ศึกษาการกำจัดฝุ่นขนาด 2.5 ไมครอนในหอบำบัดแบบเปียกขนาดความสูง 4 เมตร หน้าตัดเป็นสี่เหลี่ยมจัตุรัสยาวด้านละ 0.85 เมตร พบว่า อัตราส่วนของน้ำกับอากาศ และระดับของน้ำที่อยู่เหนือหัวกระจายอากาศ มีผลต่อประสิทธิภาพการกำจัดฝุ่น โดยฝุ่นขนาด 2.5 ไมครอนถูกป้อนจากจากท่อไอเสียรถยนต์ดีเซลที่ผ่านใช้งานมาแล้ว โดยเมื่อเพิ่มอัตราส่วนของน้ำกับอากาศ และการเพิ่มระดับน้ำเหนือหัวกระจายอากาศจะเป็นการเพิ่มประสิทธิภาพการกำจัดฝุ่นขนาด 2.5 ไมครอน โดยเมื่อเริ่มต้นการเดินระบบหอบำบัดอากาศแบบเปียกด้วยอัตราส่วนน้ำต่ออากาศ 5.14 ลิตรต่อลูกบาศก์เมตร ระดับน้ำเหนือหัวกระจายอากาศ 150 มิลลิเมตร ทำให้เกิดความต้านทานอากาศจากระบบปั่นป่วนน้ำและทำให้อัตราการไหลอากาศลดลง และเกิดการผสมผสานระหว่างน้ำและอากาศในภาวะปั่นป่วน ทำให้ได้อัตราส่วนของน้ำต่ออากาศ เพิ่มสูงขึ้นเป็น 9.03 ลิตรต่อลูกบาศก์เมตร และให้ประสิทธิภาพเฉลี่ยการกำจัดฝุ่นขนาด 2.5 ไมครอนเพิ่มขึ้นสูงถึง 87.3 % เมื่อนำภาวะดำเนินการนี้ไปใช้กับหอบำบัดแบบเปียกในภาคสนามที่มีลักษณะและขนาดเท่ากัน โดยติดตั้งบริเวณที่พักผู้โดยสารริมถนนในเขต

เมืองจังหวัดพิษณุโลกที่มักจะมีค่าฝุ่นขนาด 2.5 ไมครอนเกินมาตรฐาน พบว่าหอบำบัดแบบเปียกแบบระบบน้ำไฮบริดทำงานโดยสามารถวัดประสิทธิภาพจากระบบอินเทอร์เน็ตของสรรพสิ่งแบบตามเวลาจริง(real-time)ซึ่งสามารถวัดประสิทธิภาพเฉลี่ยการกำจัดฝุ่นขนาด 2.5 ไมครอน ได้ร้อยละ 85 โดยพบปริมาณลดความเข้มข้นของฝุ่นขนาด 2.5 ไมครอน หลังการบำบัดด้วยวิธีการนี้มีค่าน้อยกว่า 15 ไมโครกรัมต่อลูกบาศก์เมตรเป็นค่าน้อยกว่าค่ามาตรฐานที่กำหนดโดยองค์การอนามัยโลก และกรมควบคุมมลพิษของประเทศไทย ซึ่งกำหนดระดับเกณฑ์มาตรฐานของฝุ่นขนาด 2.5 ไมครอน มีค่าต่ำกว่า 37.5 ไมโครกรัมต่อลูกบาศก์เมตร

คำสำคัญ: ฝุ่นขนาด 2.5 ไมครอน ประสิทธิภาพการบำบัด ระบบฟอกอากาศ หอบำบัดอากาศแบบเปียก อินเทอร์เน็ตของสรรพสิ่ง

Abstract

This research aims to improve the air quality at bus shelters near roads to protect people from PM2.5 pollution by proposing the development of a wet scrubber that integrates IoT-based methods for measuring the quality of clean air at airflow outlets and PM2.5 removal efficiency in real-time via the combination of turbulent water and a spray wet scrubber. This research was divided into two parts: indoor laboratory and outdoor bus shelter experiments, which used the exact reactor size. The investigated parameters for the indoor experiment were the liquid-to-air ratio and water level above the nozzle using the old diesel pickup truck generating PM2.5. The effects of both parameters on the average PM2.5 removal efficiency were investigated in a wet scrubber with a height of 4 m and a height of 0.85 m on one side of a square section. An increasing liquid-to-air ratio and water level above the nozzle favored increasing PM2.5 removal efficiency. In addition, it was also concluded that starting with 5.14 l/m^3 of liquid-to-air and 150 mm of water above the nozzle created a final liquid-to-air ratio of 9.03 l/m^3, which gave an average PM2.5 removal efficiency of 87.3%. This condition was applied for operating another wet scrubber with an IoT-based system installed outdoors at the bus shelter near the road in the center of Phitsanulok City, where the PM2.5 concentration exceeded the standard. The results showed that the wet scrubber IoT-based system has a PM2.5 removal average efficiency of more than 85% or a PM2.5 concentration after treatment below 15 $\mu g/m^3$, which meets the standards of the World Health Organization and the Pollution Control Department of Thailand (below 37.5 $\mu g/m^3$).

Keywords: PM 2.5, removal efficiency, air purification, wet scrubber, IoT sensor

1. Introduction

The PM 2.5 problem has affected the well-being of urban people in terms of the health economy. The World Health Organization (WHO) announced this in 2016. The impact of outdoor pollution is estimated to cause three million deaths annually. In particular, PM2.5 has risen among the world's five most lethal risk factors. In 2016, 4.2 million deaths were caused by PM2.5 worldwide, and 91% of these people lived in Asian countries and the West Pacific [1]. The deaths were attributed to short-term exposure to outdoor PM. Therefore, PM2.5 pollution has become a top concern for the public in some urban centers and near traffic areas, especially where high concentrations of particulate matter occur; importantly, this pollution negatively affects social and economic activity worldwide. In Thailand, there is awareness of the problem of pollution from PM

2.5 and PM 10 dust, which affects people's health and the Thai economy, from the individual and household levels to the national level. Thailand would have sustained a THB of 1.79 trillion or 11.62 of the country's GDP as a result of societal damage due to PM10 pollution in 2017 [2]. PM2.5 will allow us to make predictions of its effects. OMC should have more impact on the economy than PM10. Bangkok's emissions originate from automobile fumes from transport and biomass combustion. In the dry season, 45% of PM2.5 is generated by diesel-powered vehicles [3]. To address the effects of air pollution, governments and the private sector are working together to develop clean air acts and plans to mitigate the impact. Thailand's national air quality standards are weak compared to the World Health Organization's recommendations. As shown in Table 1, the annual mean for the most dangerous pollutant, PM2.5, is 25 micrograms per cubic meter (μg/m^3), 5 times greater than the WHO guideline. The daily standard is 50 μg/m^3, 3.3 times higher than that of the World Health Organization (WHO) [2,4].

Table 1 PM2.5 Air Quality Index, Thailand, and WHO

Standard	Data curation	PM 2.5 (μg/m^3)
THAILAND	Annual mean	25
	24-hour mean	50
The World Health Organization	Annual mean	5
	24-hour mean	15

This research aimed to develop a wet spay scrubber system that uses turbulent water techniques combined with an IoT system to monitor the quality of PM2.5 dust pollution and control the operating conditions of wet spay scrubbers in accordance with the amount of pollution to reduce PM2.5 pollution in bus shelter areas, which affects the health of urban residents. Therefore, the IoT system can monitor the efficiency of hybrid wet scrubbers by measuring PM2.5 dust pollution in real time, which enables monitoring and improving air quality in bus shelters by reducing PM 2.5 dust pollution from roadside traffic in Phitsanulok city.

2. Methodology

Development of the IoT-based Hybrid Wet Scrubber Tower for PM 2.5 Removal

The proposed hybrid wet scrubber combines turbulent and spray wet scrubber technology in this section. Moreover, Internet of Things (IoT) technology has also been integrated with the proposed wet scrubber to study behavior and PM2.5 removal efficiency.

2.1 Design of the Hybrid Wet Scrubber Tower

End-of-pipe technology as an air pollution control device to eliminate dust and PM2.5 from air pollutants have many advantages, such as Cyclone's efficiency in filtering dirty air, which is 90%. However, it can only filter dust particles with diameters greater than 20 μm. The spray tower removal efficiency can reach 90% for particles larger than 5 μm—and the removal efficiency can reach 3 to 5 μm for particles with diameters ranging from 60 to 80%. Below 3 μm, the removal efficiency decreases to less than 50%. The venture scrubber efficiency is 98%, and the material can be filtered to 0.5 μm. The efficiency of the electrostatic precipitator in filtering dirty air was 99%. It can filter dust at a 1 μm diameter but consumes a high amount of power. The other is Baghouse, whose efficiency in filtering polluted air is nearly 100%. It can filter dust with a diameter of 1 μm, but this technology has high airflow resistance and is expensive to use and maintain [5-7]. A counterflow wet scrubber was selected and developed to increase its efficiency in removing PM2.5 along the roadside, as it is convenient for operation and maintenance. PM2.5 along the roadside in Phitsanulok City was selected as the place where the wet scrubber was installed.

This wet scrubber's design relies on the knowledge of the absorption tower and relies on the design of the dissolved gas evaporator as a guideline [8]. As a wet scrubber uses liquid to remove pollutants, called the scrubbing process, two fundamental removal mechanisms are associated with particle removal from the process stream in the scrubber, namely, impact and Brownian diffusion. Kim et al. [9] conducted a theoretical analysis of the particle removal efficiency of a gravitational wet scrubber considering impaction, interception, and diffusion. The turbulent water technique for this absorption tower was also included in this design. This technique creates a deflector and baffle to make the water turbulent. The water is turbulent, and the polluted air flows through the fluctuating water. This method can simultaneously increase the wettability of particles, cause agglomeration, and remove dust [10]. Meikap et al. [11] achieved a removal efficiency of 95-99% for particulate matter sizes ranging from 0.1 μm to 100 μm in a modified multistage bubble column scrubber. Park and Lee [12] reported that a swirling cyclone wet scrubber can collect particles with a 2.5 μm efficiency of 86% and a 5 μm efficiency of 97%. Park and Lee [13] reported that aerosols polydispersed by wet scrubbing can remove more than 90% of particles with a size greater than 2 μm. Raj Mohan et al. [14] reported that a particulate removal efficiency of approximately 75–99% was achieved using a novel spray-cum-bubbler scrubber. The results show that the bubble column removes the maximum number of particles when the concentration increases. Byeong-Kyu Lee [10] studied the performance of a water turbulence scrubber for removing particulate matter. They found that particles more than one μm in diameter were drawn very efficiently, at nearly 100%, depending upon the flow rate, the dust-laden air stream concentration, and the reservoir water level. Hence, spray columns and bubble column scrubbers are more convenient for scrubbing particulate matter from effluent. Thus, particles are conditioned during scrubbing by wetting them, entrapping them in water blankets, and impacting them with water droplets. After receiving the effective parameter for removing dust, the PM2.5 absorption tower diagram combines both mechanisms into the hybrid wet scrubber tower shown in Figure 1 and the turbulence box shown in Figure 2. The summary design parameters of the proposed hybrid wet scrubber tower are shown in Table 2.

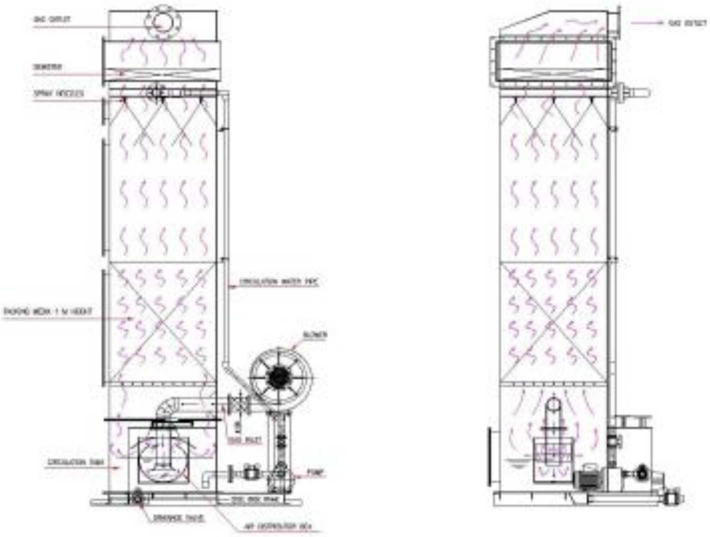

Figure 1 Hybrid wet scrubber tower

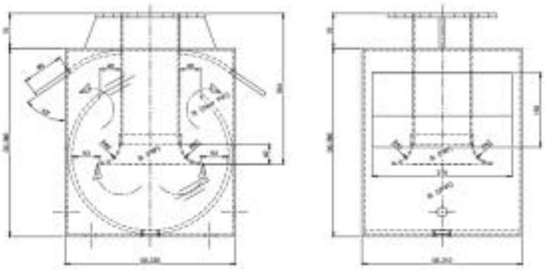

Figure 2 Turbulence box inside the hybrid wet scrubber tower

Table 2 Summary of Hybrid Wet Scrubber Towers

Parameter	Value
Height of the tower	4 m.
Width of the tower (Square)	0.85 m.
Height of Transfer Unit	2 m.
The spray head is 270 μm	12 pcs
Liquid-to-Air Ratio	Up to 13.21 L/m3
Pressure Drop of water spray tower	12.11 cm. W.C
Pressure Drops increased by The Turbulent	10-15 cm. W.C.
Blower with inverter	1 hp
Water Pump	1 hp
Water Tank	390 Liters

2.2 Design of the IoT system for real-time performance measurement

The Internet of Things (IoT) refers to devices, objects, or machines with IoT controllers, software, sensors, and network connections [15,16]. These devices can be stored and exchanged for data via wireless communication or the Internet. The data can be anything from environmental data collected through sensors or signals for remote control of the IoT device.

To collect the behavior data of the proposed hybrid wet scrubber tower for performance analysis, the authors have proposed an IoT system integrated with the tower. Figure 2 illustrates the detailed architecture of the designed IoT system.

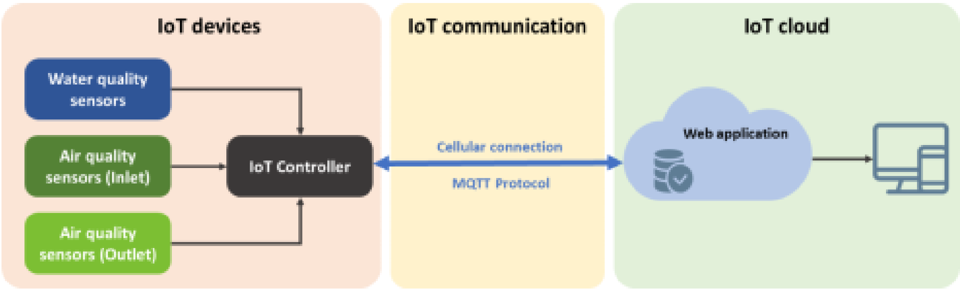

Figure 3 Architecture of the IoT system integrated with the proposed hybrid wet scrubber tower

Figure 3 illustrates the architecture of the IoT system for a hybrid wet scrubber tower. The proposed system consists of 3 layers: 1) IoT devices implemented on a wet scrubber tower, 2) IoT communication, such as protocol and network technology, and 3) an IoT cloud, which is a web application service for data collection and monitoring [17,18]. The IoT device layer contains numerous sensors connected to the wet scrubber tower needed for data collection [19]. In the water tank of the wet scrubber tower, water quality sensors were installed to collect data such as water level, pH, and electrical conductivity (EC) of water. At the inlet and outlet of the wet scrubber tower, air quality data such as the PM2.5 concentration (μg/m^3), relative humidity (%), and temperature (°C) were collected. Then, all the data collected from the sensors are processed and transmitted to the IoT cloud layer using an IoT controller, which is an industrial-grade PLC controller. The IoT communication layer refers to the communication process between IoT devices and the IoT cloud. The IoT controller in the IoT device layer was designed to connect and send all the data across cellular networks. Therefore, the MQTT protocol was essential in establishing communication between the IoT controller and the IoT cloud [20].

At the IoT cloud layer, all the data collected from the IoT device layer connected to the wet scrubber tower are processed in this part of the IoT system. The IoT cloud layer comprises a database and web application server to store the data and wait for the user to request the data display on the web browser [21].

3. Experimental procedure

The experimental setup for PM2.5 removal by the IoT system and hybrid wet scrubber, a combination of turbulent and spray wet scrubber technology, was described with testing methods for indoor and outdoor conditions.

3.1 Indoor experiment

An experimental method for indoor conditions was developed as follows.

1) The 60 m^3 experimental room was built as a controlled environment with polluted air produced from a 10-year-old pickup truck using 2500 cc diesel direct engines.

2) A prototype of the absorption tower integrated with an IoT system for real-time monitoring was installed at the wet scrubber tower's air inlet and outlet to measure PM2.5 levels. The Honeywell HPMA115S0 sensor (Honeywell International, Inc., USA.) was selected for this study. According to the EPA standard, it has proven to be a suitable sensor [22-24]. The HPMA115S0 sensor is a laser-based sensor that uses the light scattering method to measure the concentration of particles in the range of 0-1,000 μg/m^3 in a given environment. A laser light source illuminates the particle as it is pulled through the detection chamber. As particles pass through the laser beam, the light source becomes obscured, and the results are recorded on the photo or light detector. The light is then analyzed and converted to an electrical signal reflecting the particulate size and quantity to calculate concentrations in real-time. The Honeywell particle sensor provides information on the particle concentration for a given particle concentration range. The sensor can provide an accuracy between ±15 μg/m^3 for a measurement range of 0 and 1000 μg/m^3 at a controlled environmental temperature of 25°C and humidity less than 95%.

3) All the sensors are connected to the ESP-32 with the NB-IoT module for data communication over the Internet and sent to Amazon Web Services (AWS) as cloud server services.

4) The PM2.5 concentrations at the inlet and outlet were measured via real-time monitoring over 4 hours per experiment. In each experiment, the PM 2.5 dust concentration at the inlet was adjusted from 0 to 1,000 μg/m^3. The dust removal efficiency can be obtained from the formula below.

The average removal efficiency of PM2.5 was calculated as (mass concentration at the PM 2.5 inlet × mass concentration at the PM 2.5 outlet)/mass concentration at the PM2.5 inlet × 100%.

$$\eta_{PM2.5} = \frac{M_{PM2.5,i} - M_{PM2.5,o}}{M_{PM2.5,i}} x100\%$$

where $M_{PM2.5,i}$ $M_{PM2.5,o}$ and $\eta_{PM2.5}$ were computed with 15-minute intervals of data from the sensor monitor. $M_{PM2.5,i}$ and $M_{PM2.5,o}$ represent the concentrations of PM2.5 in the inlet and outlet streams and the area under the curve of the PM2.5 concentration with the interval time, respectively. The experimental setup is shown in the flow diagram in Figure 4(a), and the real situation is shown in Figure 4(b).

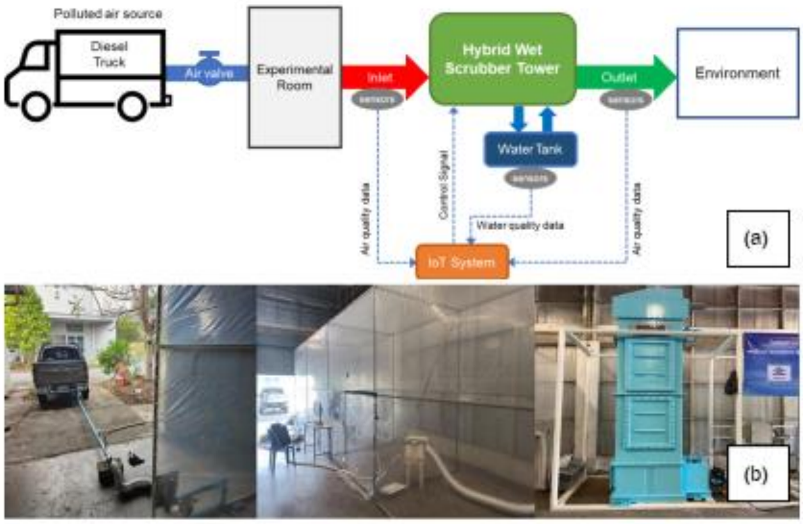

Figure 4 (a) Architecture diagram of the wet scrubber tower with an IoT system for an indoor experiment and (b) the developed wet scrubber tower installed in the indoor experimental room.

3.2 Outdoor experiment

An experimental method for outdoor conditions was developed as follows.

1) A hybrid wet scrubber tower with an IoT system was installed at the bus shelter.

2) An IoT system controls the wet scrubber tower to operate twice daily (7:00-11:00 am and 3:00-7:00 pm as busy hours) by working under the optimum conditions obtained from the indoor experiment.

3) PM2.5 concentrations at the inlet and outlet of the wet scrubber tower were measured over 4 hours of each operation and computed at 15-minute intervals from the sensor monitoring data. The PM2.5 removal efficiency $\eta_{PM2.5}$ was calculated using the same method used in the indoor experiment. Figure 5*(a)* shows the flow diagram, and 5*(b)* shows the real situation.

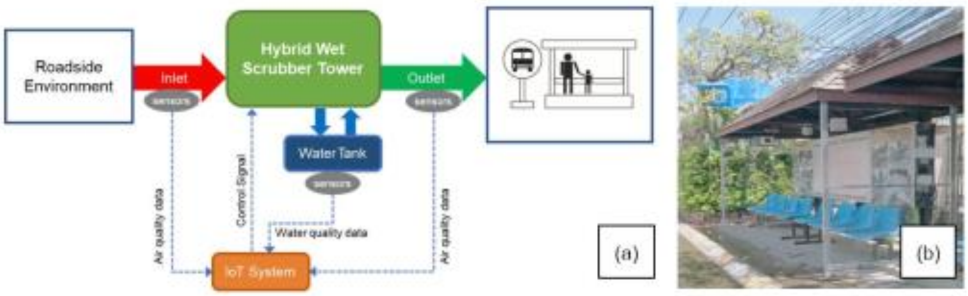

Figure 5 (a) Architecture diagram of the wet scrubber tower with an IoT system for outdoor experiments and (b) the developed wet scrubber tower installed at the bus shelter.

4. Results and discussion

The PM2.5 removal results achieved by the IoT system and hybrid wet scrubber, which are combinations of turbulent and spray wet scrubber technologies, were evaluated via experimental methods under indoor and outdoor conditions.

4.1 Performance of the proposed hybrid wet scrubber tower in the indoor experiment

The parameters for PM2.5 removal by hybrid wet scrubber towers in indoor experiments, such as the liquid-to-air ratio and water level above the nozzle, were investigated.

4.1.1 Effect of the liquid-to-air ratio on the PM2.5 removal efficiency

Two air flow rate inputs, wet scrubbers (8.51 and 3.40 CMM), and a constant water spray flow rate of 45 liters/minute, corresponding to liquid-to-air ratios of 5.41 and 13.21 l/m3, respectively, were investigated. A plot of the average removal efficiency of PM2.5 in the indoor experiment as a function of the inlet concentration range from 50 to 900 µg/m^3 and different liquid-to-air ratios of 5.14 and 13.21 l/m^3 is shown in Figure 6. The results showed that the average removal efficiency of PM2.5 when operated using only the spray scrubbing method was approximately 30% at a liquid-to-air ratio of 5.14 l/m^3. However, the average efficiency of PM2.5 removal could reach 50% by reducing the air flow rate to achieve a liquid-to-air ratio increase to 13.21 l/m^3. This could be explained by the lower air flow rate (a lower quantity of PM2.5) and greater PM 2.5 capture water capacity (still, a constant flow rate of 45 liters/minute). An increasing liquid-to-air ratio resulted in increased efficiency, which was also reported by Bashir Ahmed Danzomo [25]. The experimental outcomes were the same as those recommended by the US EPA for removing particles ranging from 3 to 5 µm in diameter and ranging from 60 to 80%. Below 3 µm, the removal efficiency decreases to less than 50% for the spray scrubbing method [5,6].

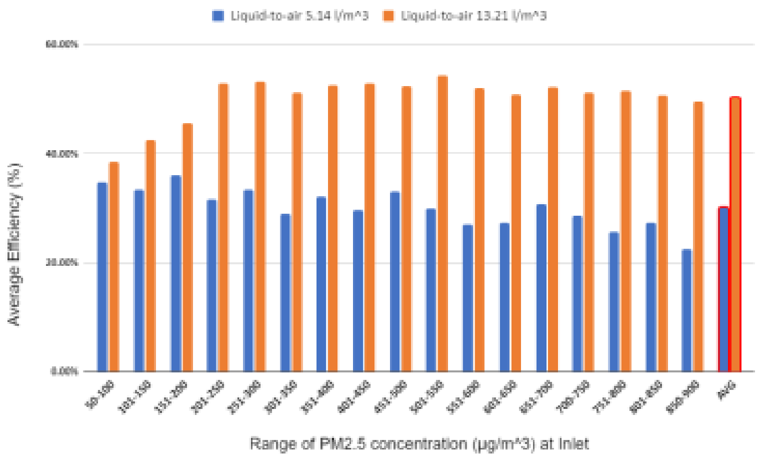

Figure 6 Comparison of the efficiencies of the proposed hybrid wet scrubber tower operated using only the spray scrubbing method at V=18 m/s (8.51 CMM) and V=7 m/s (3.40 CMM)

4.1.2 Effect of the water level above the nozzle on the PM2.5 removal efficiency

The effect of turbulence techniques creates water turbulence in this spray wet scrubber tower by installing a deflector and baffle at the airflow inlet and varying the water level above the nozzle to 50, 100, and 150 mm by keeping the initial liquid-to-air ratio at 5.14 l/m^3, which reduces the airflow velocity by the airflow resistance of water and increases the efficiency of PM 2.5 removal. The average efficiency of PM2.5 removal as a function of the inlet PM2.5 concentration ranges from 50-900 µg/m^3 and different water levels above the nozzle are shown in Figure 7. The effect of turbulent-spray water showed that the average efficiency of PM2.5 removal was more than 70% by 50 mm of water above the nozzle, more than 80% by 100 mm of water above the nozzle, and more than 85% by 150 mm of water above the nozzle. The airflow speed was reduced by the airflow resistance of water above the nozzle to create stirring water. Therefore, when the airflow speed decreases, the liquid-to-air ratio in the spray part increases, as shown in Table 3. Then, the average efficiency of the hybrid wet scrubber increased. This result was also observed by Lee B-K [9].

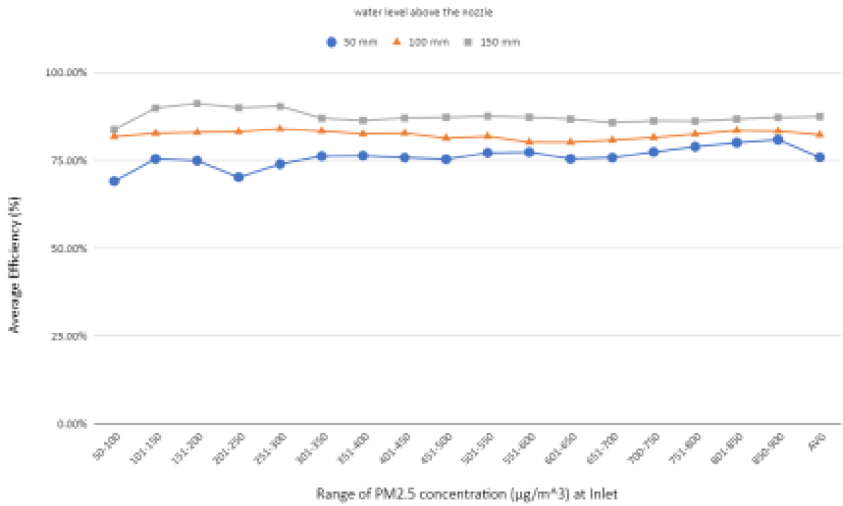

Figure 7 PM 2.5 removal efficiency of the hybrid wet scrubber at water levels above the 50-, 100-, and 150-mm nozzles.

Table 3 Increasing liquid-to-air ratio as a function of the water level above the nozzle

The water level above the nozzle (mm)	Liquid-to-air ratio (l/M^3)	Average efficiency (%)
0	5.14	30.4
50	6.38	71.7
100	7.26	80.8
150	9.03	87.3

4.2 Performance of the proposed hybrid wet scrubber tower installed at the bus shelter in the outdoor experiment

The PM2.5 concentration data collected from a bus shelter near the road in the center of Phitsanulok from January to April 2023 are shown in Figure 8. These data indicate that the PM2.5 concentration in the city can reach 223 μg/m^3, which is not more than 300 μg/m^3 according to the 24-hour average throughout the year. However, this value was six times greater than the 24-hour mean of Thailand's national air quality standards and almost 15 times greater than the WHO recommended.

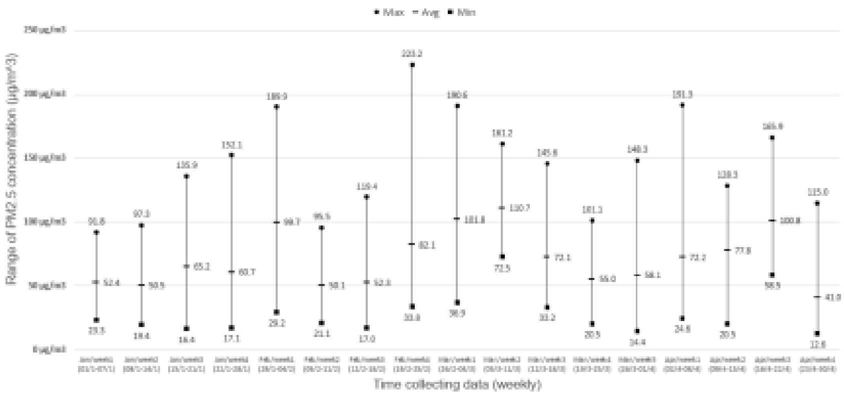

Figure 8 PM2.5 Data collected from a bus shelter near the road in the center of the Phitsanulok municipality between January and April 2023

In April, the hybrid wet scrubber was operated at an airflow rate of 3.40 CMM and 150 mm of water above the nozzle at the bus shelter. The inlet and outlet average PM2.5 concentrations of the air purification tower are shown in Figure 9. The method also performed excellently by revealing the value of clean air at an airflow outlet concentration that met WHO standards throughout the month.

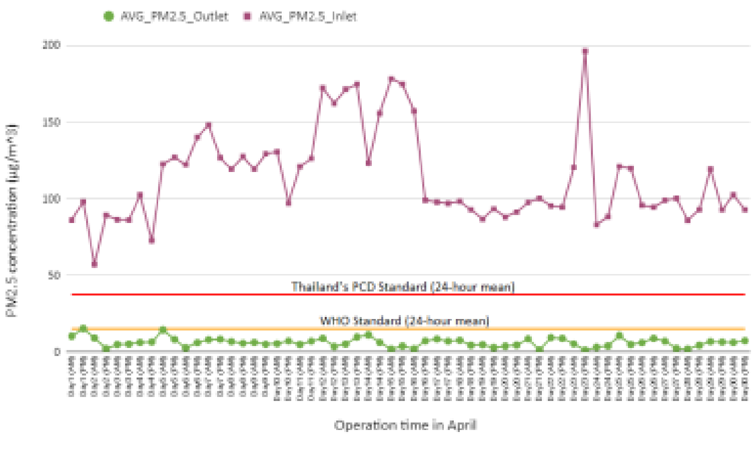

Figure 9 Results after the installation of the hybrid wet scrubber at the bus shelter in April 2023

In addition, the clean air from the purification tower, approximately three to four hundred cubic meters per hour, will be discharged into a clean air curtain, giving the bus shelter an air change rate of more than six, which will create sufficient air circulation, especially on days when there is a lot of dust and when the distribution of pollution will spread less as well from the air stable or not moving as temperature inversion. Figure 10 shows passengers in a bus shelter operating with a hybrid wet scrubber. The external air inlet installed in front of the two sides of the bus shelter and the purified air entering the roof of the shelter are shown in Figure 11.

Figure 10 Passengers waiting inside the bus shelter during the operation of the hybrid wet scrubber

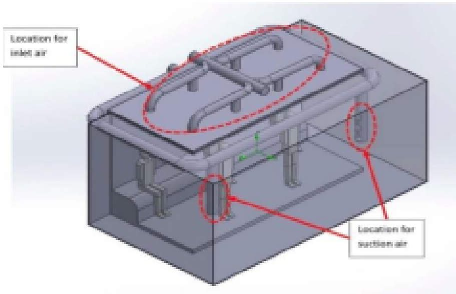

Figure 11 Position of the suction air and purified air inlet in the shelter

5. Conclusion

The PM2.5 removal results achieved by the IoT system and hybrid wet scrubber, which are combinations of turbulent and spray wet scrubber technologies, were investigated in real-time via experimental methods under indoor and outdoor conditions. Two parameters were investigated: the ratio of liquid to air and the water level above the nozzle. The performance of the hybrid wet scrubber tower is assessed by varying the liquid-to-air ratio only via the spray scrubbing method. Increasing the liquid-to-air ratio from 5.14 to 13.21 l/m^3 resulted in an average PM2.5 removal efficiency of 30 to 50% in the spray water section. The PM2.5 removal efficiency increased from 30.4 to 87.3% when the spray wet scrubber was combined with the water turbulence by setting the water level above the nozzle at 50, 100, or 150 mm. A higher water level above the nozzle creates turbulence, favoring greater PM2.5 removal efficiency. Finally, a liquid-to-air ratio of 13.21 l/m^3 and a water level above the nozzle of 150 mm were set up for the optimum parameters in another hybrid wet scrubber tower of the same size that was operated outdoors in the bus shelter. The PM2.5 concentration at the airflow outlet always met the WHO standards and The Pollution Control Department of Thailand.

Acknowledgments

This research was part of the development of an IoT-based Hybrid Wet Scrubber Tower for PM 2.5 removal at the bus shelter in Phitsanulok, Thailand, funded by the National Broadcasting and Telecommunication Commission as well as Fuels and Energy from Biomass Center, Chulalongkorn University, Saraburi, supporting the experimental facilities.

References

[1] Ali, M.A., Huang, Z., Bilal, M., Assiri, M.E., Mhawish, A., Nichol, J.E., Leeuw, G., Almazroui, M., Wang, Y., and Alsubhi, Y. (2023). Long-term PM2.5 pollution over China: Identification of PM2.5 pollution hotspots and source contributions. *Science of The Total Environment*. 893, 164871. DOI: 10.1016/j.scitotenv.2023.164871

[2] Attavanich, W., Mungkung, R., Mahathanaseth, I., Sanglestsawai, S., and Jirajari, A. (2016). Developing Green GDP Accounting for Thai Agricultural Sector Using the Economic Input-Output - Life Cycle Assessment to Assess Green Growth. In Proceedings of the SEE 2016 in conjunction with ICGSI 2016 and CTI 2016 On "Energy & Climate Change: Innovating for a Sustainable Future," Bangkok, Thailand, 28-30 November 2016, 2016.

[3] Oanh, N.T., Co, H. and Kondo, Y. (2013) Investigation on the Impacts of Urban–Rural Air Pollution on Air Quality and Climate in Southeast Asia; Asia-Pacific Network for Global Change Research: The University of Tokyo.

[4] World Health Organization. (2021) Ambient (outdoor) air pollution. Retrieved from https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health

[5] Schnelle, K.B. Jr and Brown. C.A. (2021). Air Pollution Control Technology Handbook; CRC Press.

[6] Mussatti, D., and Hemmer, P. (2022) EPA/452/B-02-001, Section 6 Particulate Matter Controls, Chapter 2 Wet Scrubbers for Particulate Matter. Retrieved from https://www.epa.gov/sites/default/files/2020-07/documents/cs6ch2.pdf

[7] EPA Office of Air Quality Planning and Standards. (1998). EPA-452/R-97-001, Stationary Source Control Techniques Document for Fine Particulate Matter; Research Triangle Park: NC.

[8] Jiuan, Y.L. (2005). Evaluation of Wet Scrubber Systems. University of Southern Queensland.

[9] Kim, H., Jung, C., Oh, S.N., and Lee, K.W. (2001). Particle Removal Efficiency of Gravitational Wet Scrubber Considering Diffusion, Interception, and Impaction. *Environmental Engineering Science*. 18(2), 125-136. DOI: 10.1089/10928750151132357

[10] Lee, B.-K., Mohan, B.R., Byeon, S.-H., Lim, K.-S., and Hong, E.-P. (2013). Evaluating the performance of a turbulent wet scrubber for scrubbing particulate matter. *Journal of the Air & Waste Management Association*. 63(5), 499-506. DOI: 10.1080/10962247.2012.738626

[11] Meikap, B.C., and Biswas, M.N. (2004). Fly ash removal efficiency in a modified multi-stage bubble column scrubber. *Separation and Purification Technology*. 36(3), 177-190. DOI: 10.1016/S1383-5866(03)00213-2.

[12] Lee, B.-K., Jung, K.-R., and Park, S.-H. (2008) Development and application of a novel swirl cyclone scrubber-(1) Experimental. *Journal of Aerosol Science*. 39(12), 1079-1088 DOI: 10.1016/j.jaerosci.2008.07.010.

[13] Park, S.-H., and Lee, B.-K. (2009) Development and application of a novel swirl cyclone scrubber: (2) Theoretical. *Journal of Hazardous Materials*. 164(1), 315-321. DOI: 10.1016/j.jhazmat.2008.08.023.

[14] Raj Mohan, B., and Meikap, B.C. (2009). Performance characteristics of the particulate removal in a novel spray-cum-bubble column scrubber. *Chemical Engineering Research and Design*. 87(1), 109-118. DOI: 10.1016/j.cherd.2008.05.011.

[15] Noura, M., Atiquzzaman, M., and Gaedke, M. (2019). Interoperability in Internet of Things:Taxonomies and Open Challenges. *Mobile Networks and Applications*. 24, 796-809.DOI:10.1007/s11036-018-1089-9.

[16] Sethi, P., and Sarangi, S.R. (2017). Internet of Things: Architectures, Protocols, and Applications. *Journal of Electrical and Computer Engineering*. 2017, 9324035. DOI: 10.1155/2017/9324035.

[17] Minerva, R., Abyi, B., and Domenico, R. (2015). Towards a definition of the Internet of Things (IoT). *IEEE Internet Initiative*. 1, 1-86. Retrieved from https://iot.ieee.org/images/files/pdf/IEEE_IoT_Towards_Definition_Internet_of_Things_Issue1_14MAY15.pdf

[18] IEEE SA Board of Governors/Corporate Advisory Group. (2019). IEEE Standard for an Architectural Framework for the Internet of Things (IoT). *IEEE Std 2413-2019*. 1-269. DOI: 10.1109/IEEESTD.2020.9032420.

[19] Cao, K., Liu, Y., Meng, G., and Sun, Q. (2020). An Overview on Edge Computing Research. *IEEE Access* 8, 85714-85728. DOI: 10.1109/ACCESS.2020.2991734.

[20] Hunkeler, U., Truong, H.L., and Stanford-Clark, A. (2008). MQTT-S — A publish/subscribe protocol for Wireless Sensor Networks. In Proceedings of the 3rd International Conference on Communication Systems Software and Middleware and Workshops. 6-10 January 2008, 791-798.

[21] Paolis, L.T.D., Luca, V.D., and Paiano, R. (2018). Sensor data collection and analytics with thingsboard and spark streaming. In Proceedings of the 2018 IEEE Workshop on Environmental, Energy, and Structural Monitoring Systems. 21-22 June 2018. 1-6.

[22] Alfano, B., Barretta, L., Del Giudice, A., De Vito, S., Di Francia, G., Esposito, E., Formisano, F., Massera, E., Miglietta, M.L., and Polichetti, T. (2020). A Review of Low-Cost Particulate Matter Sensors from the Developers' Perspectives. *Sensors*. 20(23), 6819. DOI: 10.3390/s20236819

[23] Hapidin, D.A., Saputra, C., Maulana, D.S., Munir, M.M., and Khairurrijal, K. (2019). Aerosol Chamber Characterization for Commercial Particulate Matter (PM) Sensor Evaluation. *Aerosol and Air Quality Research*. 19, 181-194. DOI: 10.4209/aaqr.2017.12.0611.

[24] Hong, G.-H., Le, T.-C., Tu, J.-W., Wang, C., Chang, S.-C., Yu, J.-Y., Lin, G.-Y., Aggarwal, S.G., and Tsai, C.-J. (2021). Long-term evaluation and calibration of three types of low-cost PM2.5 sensors at different air quality monitoring stations. *Journal of Aerosol Science*. 157, 105829. DOI: 10.1016/j.jaerosci.2021.105829.

[25] Danzomo, B.A., Salami, M., Jabirin, S., Khan, M.R., and Nor, I.M. (2012). Performance Evaluation of Wet Scrubber System for Industrial Air Pollution Control. *Journal of Engineering and Applied Science*. 7(12), 1169-1677.

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