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การกำจัดฝุ่น 2.5 ไมครอนในที่พักรถโดยสารจังหวัดพิษณุโลก ด้วยหอบำบัดแบบเปียกด้วยระบบน้ำแบบผสมผสานพร้อมระบบอินเทอร์เน็ตของสรรพสิ่ง

PM2.5 REMOVAL IN BUS SHELTER IN PHITSANULOK PROVINCE BY WET SCRUBER WITH IoT SYSTEM

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บทคัดย่อ

งานวิจัยนี้มีความมุ่งหมายที่จะปรับปรุงคุณภาพอากาศภายในที่พักผู้โดยสารรถประจำทางบริเวณริมถนนเพื่อป้องกันฝุ่นขนาด 2.5 ไมครอน โดยเสนอการพัฒนาระบบอินเทอร์เน็ตของสรรพสิ่ง (IoT) ติดตั้งกับหอบำบัดแบบเปียกที่ผสมผสานของระบบปั่นป่วนของน้ำ-อากาศเพื่อวัดประสิทธิภาพการกำจัดฝุ่นแบบตามเวลาจริง (real time) งานวิจัยนี้แบ่งเป็น 2 ส่วน คือ การทดลองโดยใช้หอบำบัดอากาศแบบเปียกขนาดเดียวกันภายใต้การจำลองในห้องปฏิบัติการ และในพื้นที่จริงบริเวณที่พักผู้โดยสารรถประจำทาง โดยตัวแปรที่ศึกษาการกำจัดฝุ่นขนาด 2.5 ไมครอน ในหอบำบัดแบบเปียกขนาดความสูง 4 เมตร หน้าตัดเป็นสี่เหลี่ยมจัตุรัสยาวด้านละ 0.85 เมตร พบว่าอัตราส่วนของน้ำกับอากาศ และระดับของน้ำที่อยู่เหนือหัวกระจายอากาศ มีผลต่อประสิทธิภาพการกำจัดฝุ่น โดยฝุ่นขนาด 2.5 ไมครอน ถูกป้อนจากจากท่อไอเสียรถยนต์ดีเซลที่ผ่านใช้งานมาแล้ว โดยเมื่อเพิ่มอัตราส่วนของน้ำกับอากาศและการเพิ่มระดับน้ำเหนือหัวกระจายอากาศจะเป็นการเพิ่มประสิทธิภาพการกำจัดฝุ่นขนาด 2.5 ไมครอน โดยเมื่อเริ่มต้นการเดินระบบหอบำบัดอากาศแบบเปียกด้วยอัตราส่วนน้ำต่ออากาศ 5.14 ลิตรต่อลูกบาศก์เมตร ระดับน้ำเหนือหัวกระจายอากาศ 150 มิลลิเมตร ทำให้เกิดความต้านทานอากาศจากระบบปั่นป่วนน้ำและทำให้อัตราการไหลอากาศลดลง และเกิดการผสมผสานระหว่างน้ำและอากาศในภาวะปั่นป่วน ทำให้ได้อัตราส่วนของน้ำต่ออากาศเพิ่มสูงขึ้นเป็น 9.03 ลิตรต่อลูกบาศก์เมตร และให้ประสิทธิภาพเฉลี่ยการกำจัดฝุ่นขนาด 2.5 ไมครอน เพิ่มขึ้นสูงเป็น 87.3% เมื่อนำภาวะดำเนินการนี้ไปใช้กับหอบำบัดแบบเปียกในภาคสนามที่มีลักษณะและขนาดเท่ากัน โดยติดตั้งบริเวณที่พัก

ผู้โดยสารริมถนนในเขตเมืองจังหวัดพิษณุโลกที่มักจะมีค่าฝุ่นขนาด 2.5 ไมครอน เกินมาตรฐาน พบว่าหอบำบัดแบบเปียกแบบระบบน้ำไฮบริดทำงานโดยสามารถวัดประสิทธิภาพจากระบบอินเทอร์เน็ตของสรรพสิ่งแบบตามเวลาจริง ซึ่งสามารถวัดประสิทธิภาพเฉลี่ยการกำจัดฝุ่นขนาด 2.5 ไมครอน ได้ร้อยละ 85 โดยพบปริมาณลดความเข้มข้นของฝุ่นขนาด 2.5 ไมครอน หลังการบำบัดด้วยวิธีการนี้มีความเข้มข้นลดลงเหลือเพียง 15 ไมโครกรัมต่อลูกบาศก์เมตร ซึ่งเป็นความเข้มข้นที่น้อยกว่าค่ามาตรฐานที่กำหนดโดยองค์การอนามัยโลกและกรมควบคุมมลพิษของประเทศไทย ซึ่งกำหนดระดับเกณฑ์มาตรฐานของฝุ่นขนาด 2.5 ไมครอน ให้มีค่าต่ำกว่า 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: PM2.5; Removal Efficiency; Air Purification; Wet Scrubber; IoT Sensor

Introduction

The particulate matter (PM) with an aerodynamic diameter of less than 2.5 μm (PM2.5) problem is considered one of the causes seriously poor air quality that affected to heath and 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, Particle matter M2.5 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 PM2.5 and PM10 dust, which affects people's health and Thailand 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 gross domestic product (GDP) as a result of societal damage due to PM10 pollution in 2017 [2]. The PM2.5 concentration levels allow us to predict the impact affected to the people's health and the impact on healthcare costs. While the formulation of PM2.5 also likely to have a greater impact on the economy than the PM10 dust. In general, both types of PM2.5 and PM10 dust are often formulated from automobile exhaust from transportation. and burning of biomass during the dry season. It is reported that approximately 45% of PM2.5 was emission from exhaust gases from fuel combustion in diesel vehicles [3]. In order 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 ($\mu g/m^3$), 5 times greater than the WHO guideline. The daily standard is 50 $\mu g/m^{3,}$ 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	PM2.5 ($\mu g/m^3$)
THAILAND	annual mean	25
	24-hour mean	50
The World Health Organization	annual mean	5
	24-hour mean	15

Objectives

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 PM2.5 dust pollution from roadside traffic in Phitsanulok city.

Methods

Development of the IoT-based Hybrid Wet Scrubber Tower for PM2.5 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.

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.

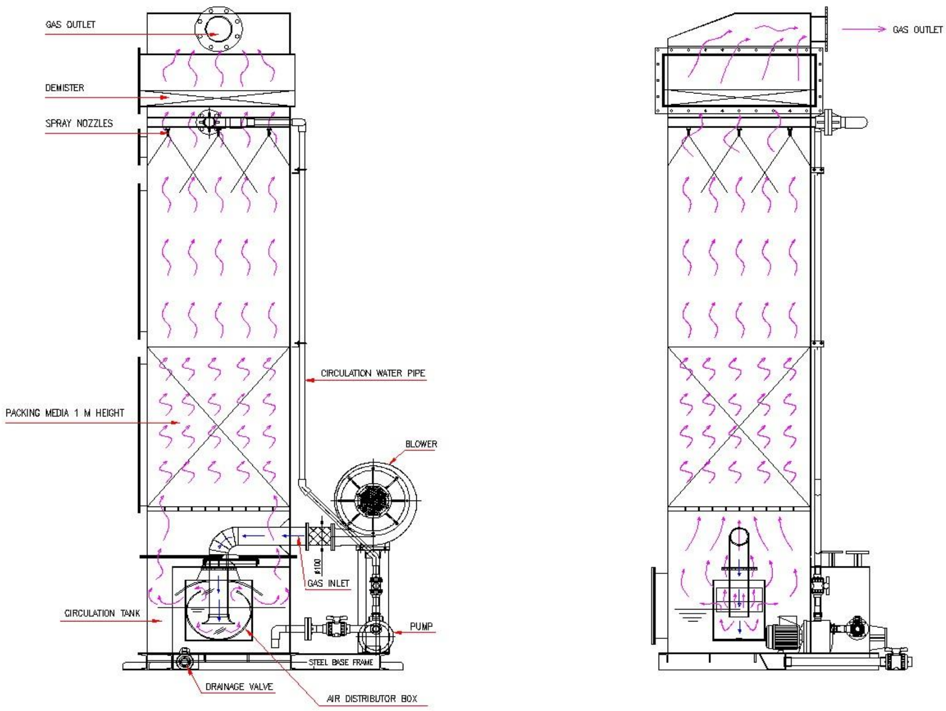

Figure 1 Hybrid wet scrubber tower

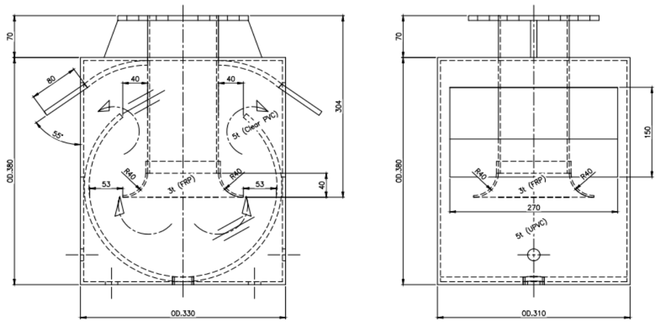

Figure 2 Turbulence box inside the hybrid wet scrubber tower.

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]. Several studies illustrated that 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 [11] and a swirling cyclone wet scrubber can collect particles with a 2.5 μm efficiency of 86% and a 5 μm efficiency of 97% [12]. While the results of aerosols polydispersed by wet scrubbing can remove more than 90% of particles with a size greater than 2 μm [13]. Furthermore, Raj Mohan et al. reported that a particulate removal efficiency of approximately 75–99% was achieved using a novel spray-cum-bubbler scrubber [14]. The results show that the bubble column removes the maximum number of particles when the concentration increases. The study of the performance of a water turbulence scrubber for removing particulate matter found that particles more than 1 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 [10]. 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.

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/m^3
Pressure drops 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

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.

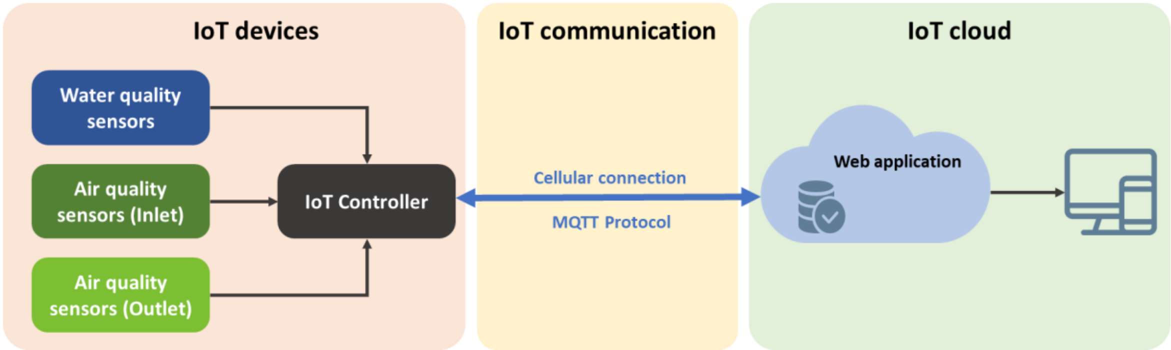

Figure 3 Architecture of the IoT system integrated with the proposed hybrid wet scrubber tower.

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 programmable logic controller (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 message queuing telemetry transport (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].

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.

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 United State Environmental Protection Agency (US.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 PM2.5 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 by $\eta_{PM2.5} = \frac{M_{PM2.5,i} - M_{PM2.5,o}}{M_{PM2.5,i}} x100\%$

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 was carried out in the pilot experimental at the centre of Fuels and Energy from Biomass, Chulalongkorn University as shown in Figure 4(b).

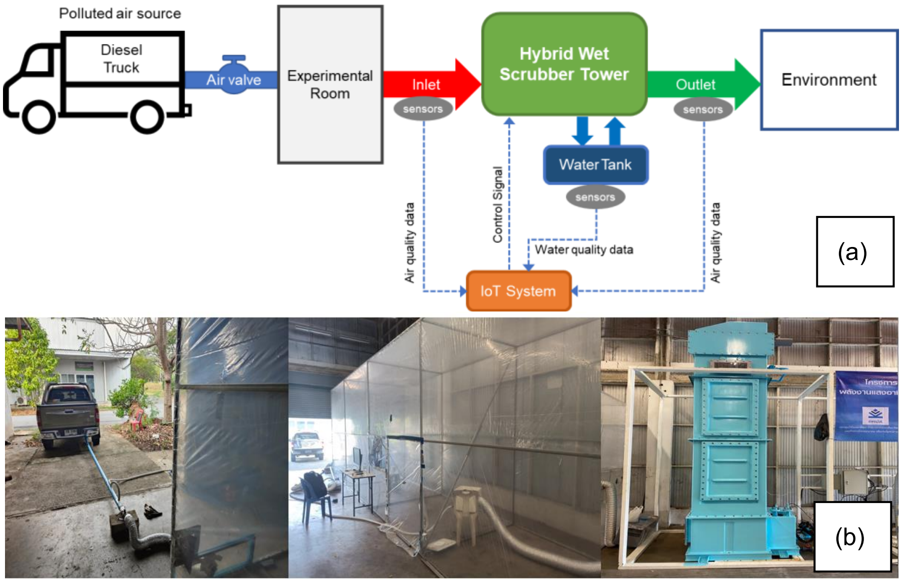

Figure 4 (a) Architecture diagram of the wet scrubber tower with an IoT system for an indoor experiment and (b) The developed wet scrubber tower installed in the indoor experimental room.

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 peak 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 Figure 5*(b)* shows the real situation.

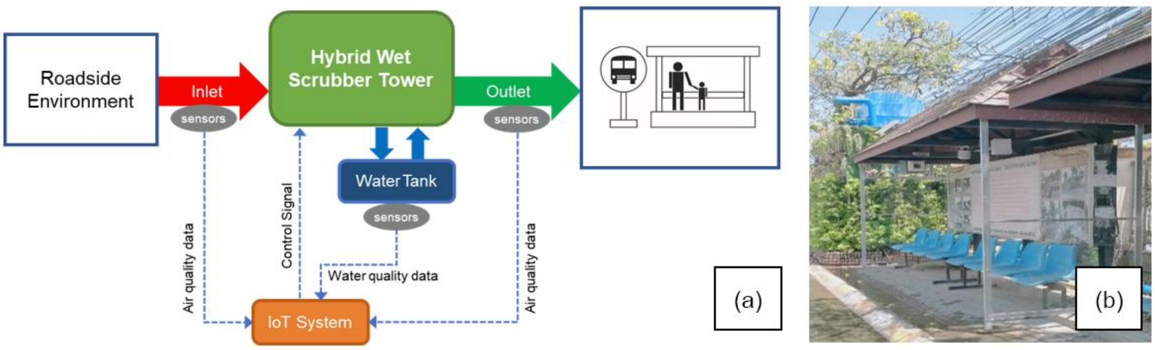

Figure 5 (a) Architecture diagram of the wet scrubber tower with an IoT system for outdoor experiments and (b) The developed wet scrubber tower installed at the bus shelter.

Results

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.

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.

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

Two air flow rate inputs, wet scrubbers at the capabilities of 8.51 and 3.40 m^3/min (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/m^3, respectively, were performed investigate. 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 PM2.5 capture water capacity (at a constant flow rate of 45 liters/minute). An increasing liquid-to-air ratio resulted in increased efficiency represented that 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% [25]. Below 3 μm, the removal efficiency decreases to less than 50%for the spray scrubbing method [5, 6].

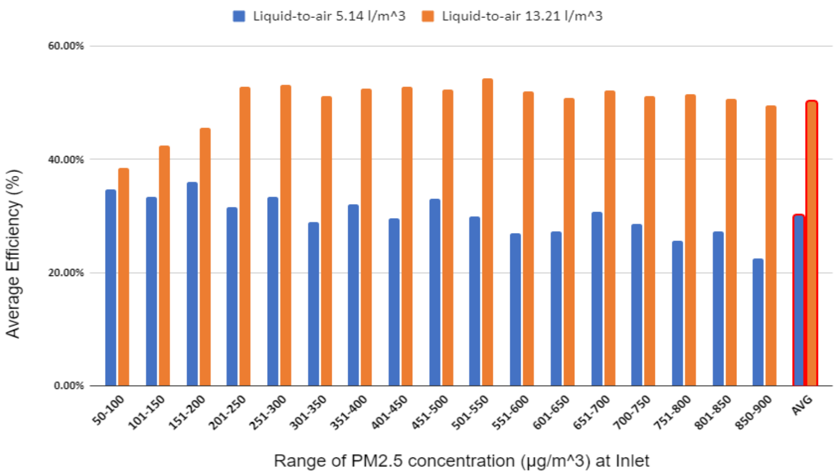

Figure 6 Comparison of the efficiencies of the proposed hybrid wet scrubber tower operated using only the spray scrubbing method at V=18 m/s (8.51 CMM) and V=7 m/s (3.40 CMM).

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 PM2.5 removal. The average efficiency of PM2.5 removal as a function of the inlet PM2.5 concentration range 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 are represented in Table 3. Then, the average efficiency of the hybrid wet scrubber increased corresponding to the study by Lee [9].

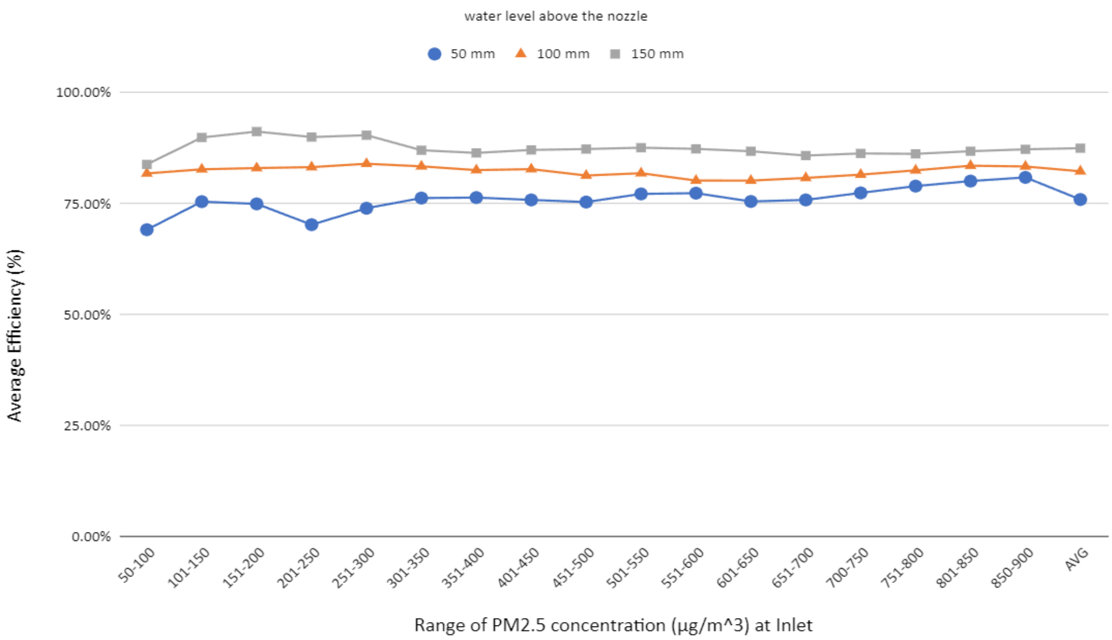

Figure 7 PM2.5 removal efficiency of the hybrid wet scrubber at water levels above the 50 mm, 100 mm, and 150-mm nozzles.

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

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 central 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.

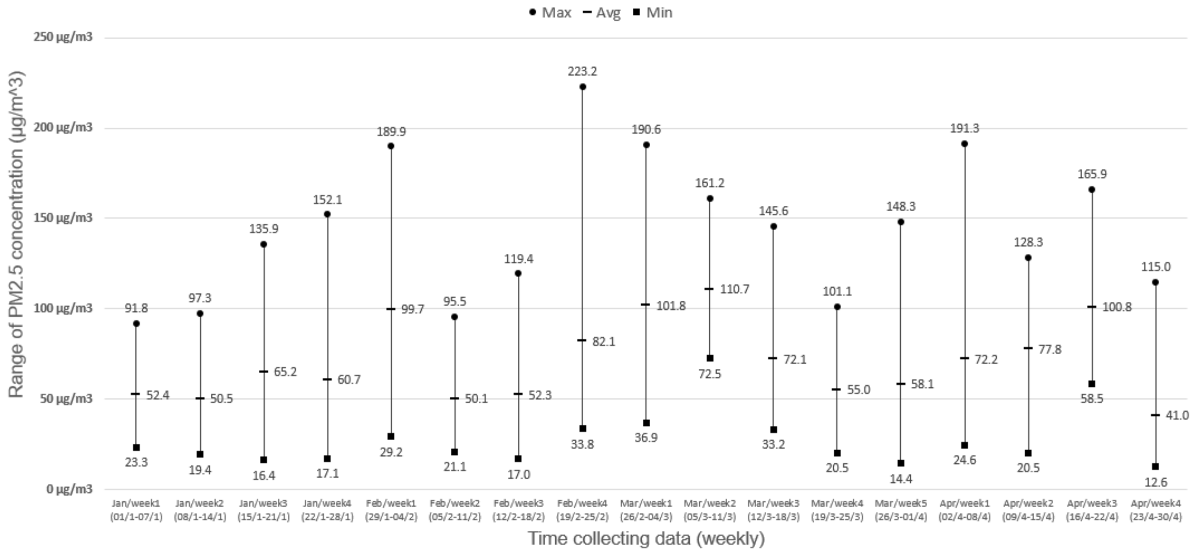

Figure 8 PM2.5 Data collected from a bus shelter near the road in the center of the Phitsanulok municipality between January and April 2023.

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.

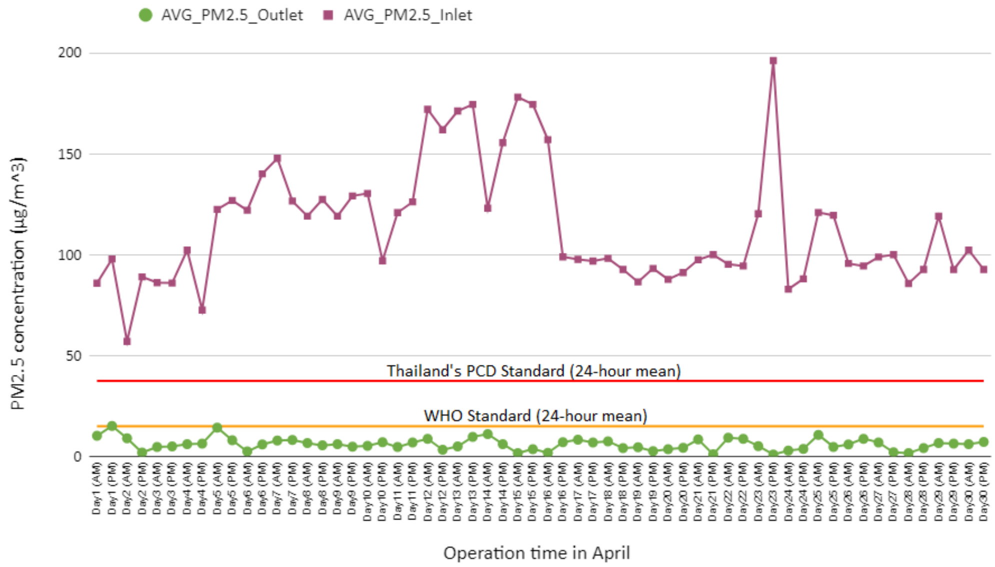

Figure 9 Results after the installation of the hybrid wet scrubber at the bus shelter in April 2023.

Conclusions 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 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. 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. The performance study of the hybrid wet scrubber tower that installed at the bus shelter in the outdoor experiment illustrated that the inlet and outlet average PM2.5 concentrations of the air purification tower performance excellently revealing the PM2.5 concentration and quality of clean air at an airflow outlet concentration that not exceed than that both of WHO standards and the Pollution Control Department of Thailand.

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

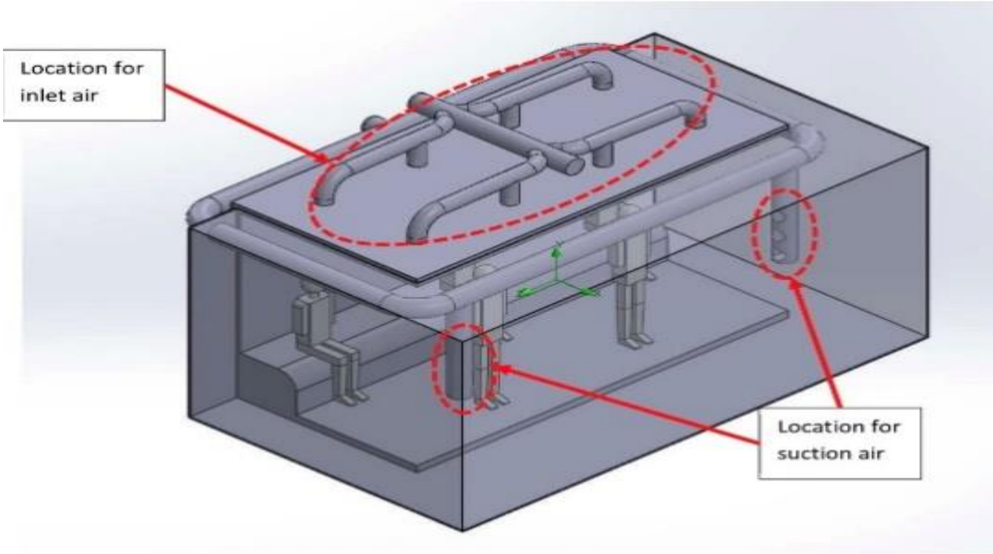

Figure 11 Position of the suction air and purified air inlet in the shelter.

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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*, Article number 164871. https://doi.org/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.

[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. https://doi.org/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. https://doi.org/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. https://doi.org/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. https://doi.org/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. https://doi.org/10.1016/j.jhazmat.2008.08.023

[14] Mohan, B. R., 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. https://doi.org/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. https://doi.org/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*, Article number 9324035. https://doi.org/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. https://doi.org/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. https://doi.org/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, pp. 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. pp. 1-6.

[22] Alfano, B., Barretta, L., Giudice, A. D., De Vito, S., Francia, G. D., 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), 1-56. Article number 6819. https://doi.org/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. https://doi.org/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*, Article number 105829. https://doi.org/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.