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Retraction

Retracted: Efficient Monitoring and Adaptive Control of Indoor Air Quality Based on IoT Technology and Fuzzy Inference

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This article has been retracted by Hindawi following an investigation undertaken by the publisher [1]. This investigation has uncovered evidence of one or more of the following indicators of systematic manipulation of the publication process:

(1) Discrepancies in scope
(2) Discrepancies in the description of the research reported
(3) Discrepancies between the availability of data and the research described
(4) Inappropriate citations
(5) Incoherent, meaningless and/or irrelevant content included in the article
(6) Peer-review manipulation

The presence of these indicators undermines our confidence in the integrity of the article's content and we cannot, therefore, vouch for its reliability. Please note that this notice is intended solely to alert readers that the content of this article is unreliable. We have not investigated whether authors were aware of or involved in the systematic manipulation of the publication process.

Wiley and Hindawi regrets that the usual quality checks did not identify these issues before publication and have since put additional measures in place to safeguard research integrity.

We wish to credit our own Research Integrity and Research Publishing teams and anonymous and named external researchers and research integrity experts for contributing to this investigation.

The corresponding author, as the representative of all authors, has been given the opportunity to register their agreement or disagreement to this retraction. We have kept a record of any response received.

References

[1] L. Zhao, H. Zhou, R. Chen, and Z. Shen, "Efficient Monitoring and Adaptive Control of Indoor Air Quality Based on IoT Technology and Fuzzy Inference," *Wireless Communications and Mobile Computing*, vol. 2022, Article ID 4127079, 14 pages, 2022.

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Research Article

Efficient Monitoring and Adaptive Control of Indoor Air Quality Based on IoT Technology and Fuzzy Inference

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In recent years, more and more occupants have suffered from respiratory illness due to poor indoor air quality (IAQ). In order to address this issue, this paper presents a method to achieve efficient monitoring and adaptive control of IAQ. Firstly, an indoor air quality monitoring and control system (IAQMCS) is developed using IoT technology. Then, based on fuzzy inference, a novel fuzzy air quality index (FAQI) model is proposed to effectively assess IAQ. Furthermore, a simple adaptive control mechanism, called SACM, is designed to automatically control the IAQMCS according to a real-time FAQI value. Finally, extensive experiments are performed by comparing with regular control (time-based control), which show that our proposed method effectively measures various air parameters (CO_2, VOC, HCHO, $PM_{2.5}$, PM10, etc.) and has good performance in terms of evaluation accuracy, average FAQI value, and overall IAQ.

1. Introduction

It is reported that 90% of the world's population breathes polluted air, causing 7 million deaths annually. Nowadays, poor air quality has emerged as one of the biggest global environmental issues [1, 2]. Compared with outdoor air quality, indoor air quality (IAQ) is more significant because people spend nearly 80% of their time staying in indoor environments (homes, schools, offices, and so on) [3, 4]. Therefore, there is an urgent need to conduct effective IAQ monitoring and control for avoiding respiratory illness and protecting people's health [5, 6].

In recent years, researchers all over the world have proposed various IAQ monitoring systems. For instance, An and Chung [7] proposed a wavelength division multiplexing optical transmission system for electromagnetic interference-free indoor dust monitoring, which can only collect indoor $PM_{2.5}$ concentration. Jo et al. [8] proposed an IoT-based indoor air quality monitoring platform, enabling users to monitor indoor air quality in anywhere and anytime. However, this platform can only perceive the indoor air quality but incapable of adjusting it. Benammar et al. [9] presented an IAQM (indoor air quality monitoring) system to realize the measurement of CO_2, CO, SO_2, NO_2, O_3, Cl_2, temperature, and relative humidity. Nevertheless, the concentration of CO, SO_2, and Cl_2 in the indoor environment is not very high, meaning that air parameters selected by the IAQM system are unreasonable. Arroyo et al. [10] developed a wireless gas sensor network system with low cost, small size, and low energy consumption, which can detect the concentration of VOC (volatile organic compounds), toluene, ethylbenzene, and xylene in the room. However, for ordinary indoor scenario, the level of toluene, ethylbenzene, and xylene is relatively low; hence, this system is only suitable for some specific pollutant detection application. Kim et al. [11] designed and implemented an integrated sensing system for real-time indoor air quality monitoring, which can detect the concentration of 7 common gases in real time and provide overall air quality alert timely. By using an extended fractional-order Kalman filter (EFKF), Ha et al. [12] merged indoor air quality index (IAQI) and humidex into an enhanced indoor air quality index (EIAQI) and proposed an

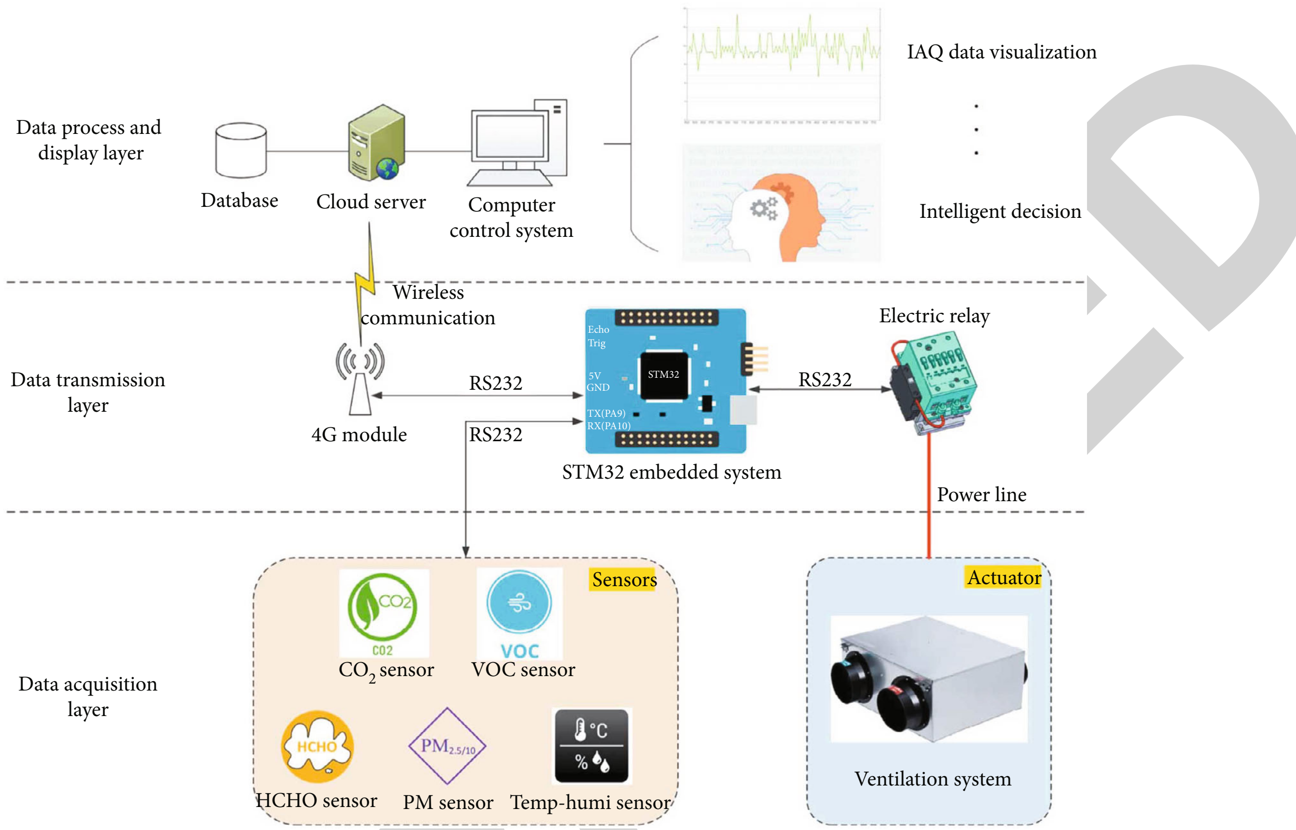

Figure 1: Architecture of the proposed IAQMCS system.

EIAQI-based air quality management system, realizing the accurate prediction of indoor air quality. Zhao et al. [13] designed an IoT-based indoor air quality detector (IAQD) with multiple communication interfaces such as Modbus, LoRa, WiFi, general packet radio service, and NB-IoT. The IAQD allows users to remotely track the IAQ status and supports various communication scenarios such as wired communications, short-range wireless communications, and remote transmission to the cloud. Dhingra et al. [14] proposed an IoT-based mobile air pollution detection system, which mainly aimed at the detection of outdoor air quality, not indoor air. By using distributed deep reinforcement learning, Hu et al. [15] proposed a mobile robots-assisted cooperative indoor air quality sensing system, called AirScope, which can effectively reduce the data latency.

According to above literature review, most of existing works focus on the monitoring/measurement of IAQ but ignore its control and regulation. Up to date, there are a few references investigating the control problem of IAQ. Fermo et al. [16] improves indoor air quality by using air purifiers (AP); AP can effectively reduce the concentration of indoor particulate matter (PM) and VOC but cannot reduce the concentration of CO_2. Ali et al. [17] introduced an open-source hardware and software platform for monitoring buildings, called Elemental. Elemental can adjust indoor CO_2 level, temperature, and humidity by controlling HVAC, but it cannot improve formaldehyde, $PM_{2.5}$, VOC, and other air pollutants. Based on multiagent theory, Chen and Chen [18] constructed an indoor air quality control system, which can calculate the collected air data and use agents to make reasonable control decisions according to the prewritten rules. However, this system only stays at the level of theoretical simulation, and its effectiveness and stability need to be further verified in real application scenarios.

In order to improve indoor air quality, it is necessary to evaluate it accurately and scientifically. The evaluation methods of indoor air quality include subjective evaluation method (using human sensory organs to describe and evaluate) and objective evaluation method (using sensors to directly measure pollutant concentration) [19]. Kraus and Nováková [20] introduced a classroom air quality evaluation method that relies on students' subjective feelings. However, students will have different reactions due to different factors such as their mental state, learning pressure, and gender, resulting in inaccurate evaluation results. Fuzzy comprehensive evaluation is a popular method to objectively evaluate air quality using fuzzy mathematics [21]. Olvera-García et al. [22] proposed an air quality evaluation method based on a weighted fuzzy inference system, which is mainly aimed at the comprehensive evaluation of urban (outdoor) air quality, and is not suitable for air evaluation in indoor scenes such as classrooms, home, and office. On this basis, Dionova et al. [23] proposed an environment indoor air quality index (EIAQI) by combining indoor air quality index (IAQI) and thermal comfort index (TCI), but the membership function of some indoor air pollutants in EIAQI is selected inappropriately.

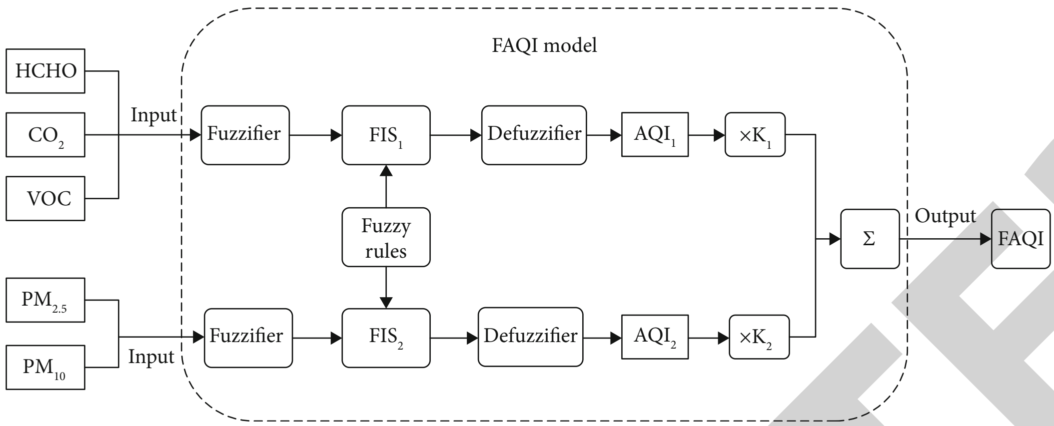

FIGURE 2: FAQI model for evaluating indoor air quality.

As far as we can see, this paper provides the following two contributions: (1) We design an IoT-based indoor air quality monitoring and control system (IAQMCS), which allows users to not only remotely check real-time/historic air quality status but also control it. (2) We propose a novel fuzzy air quality index (FAQI) model to effectively assess indoor air quality. Based on the calculated FAQI value, a simple adaptive control mechanism, called SACM, is designed to automatically control the IAQMCS system to improve indoor air quality.

The remainder of this paper is organized as follows. Section 2 introduces the architecture of the proposed IAQMCS system. Section 3 describes the design of FAQI model and SACM mechanism. Section 4 evaluates the simulation and experimental results, respectively. Finally, Section 5 concludes the paper and presents our future work.

2. Architecture of the Proposed IAQMCS System

Based on the understanding of IoT elements in [24, 25], we design the architecture of an IoT-based indoor air quality monitoring and control system (IAQMCS), as shown in Figure 1. The proposed IAQMCS system can be divided into three layers [26, 27]:

(1) Data acquisition layer: this layer uses various gas sensors to collect common air parameters such as CO_2, VOC, HCHO (formaldehyde), $PM_{2.5/10}$, temperature, and humidity. Besides, a ventilation system is used as an actuator to improve indoor air

(2) Data transmission layer: this layer consists of a STM32 embedded system, a 4G module, and an electric relay. The STM32 embedded system transmits indoor air data collected by sensors to remote cloud server through 4G module. And the STM32 also controls the working state of ventilation system through electric relay

(3) Data process and display layer: this layer includes a database, a cloud server, and a computer control system. The database stores massive air quality and other kinds of data, and the cloud server analyzes and processes these big data. The computer control system uses predefined fuzzy logic rules to calculate the evaluation result of air quality in an indoor environment, downloads control decision to STM32 to automatically adjust the ventilation system, and provides the visualization of real-time/historic IAQ data

TABLE 1: Value range of actual input and output parameters.

Parameter category	Parameters	Value range
Input	HCHO	$0 \sim 0.25\ mg/m^3$
	CO_2	$0 \sim 2000$ ppm
	VOC	$0 \sim 0.8\ mg/m^3$
	$PM_{2.5}$	$0 \sim 300\ \mu g/m^3$
	PM_{10}	$0 \sim 500\ \mu g/m^3$
Output	AQI_1	$0 \sim 400$
	AQI_2	$0 \sim 400$

3. Design of FAQI Model and SACM Mechanism

3.1. Design of FAQI Model. In order to solve the drawbacks such as unreasonable input parameters, poor comprehensiveness, and low accuracy in existing air quality fuzzy evaluation methods, a novel fuzzy air quality index (FAQI) model is designed, as shown in Figure 2.

The inputs of the FAQI model are divided into two categories: (1) air pollutants and (2) inhalable particulate matters. Air pollutants include HCHO, CO_2, and VOC, while inhalable particulate matters include $PM_{2.5}$ and PM_{10}. By fuzzification operation, these physical inputs can be translated into fuzzy inputs. Then, based on predefined fuzzy rules, the fuzzy inference system (FIS) determines fuzzy output according to fuzzy inputs. After defuzzification operation, fuzzy output can be converted into sharp output (AQI_1/AQI_2). Finally, the total assessment result FAQI is

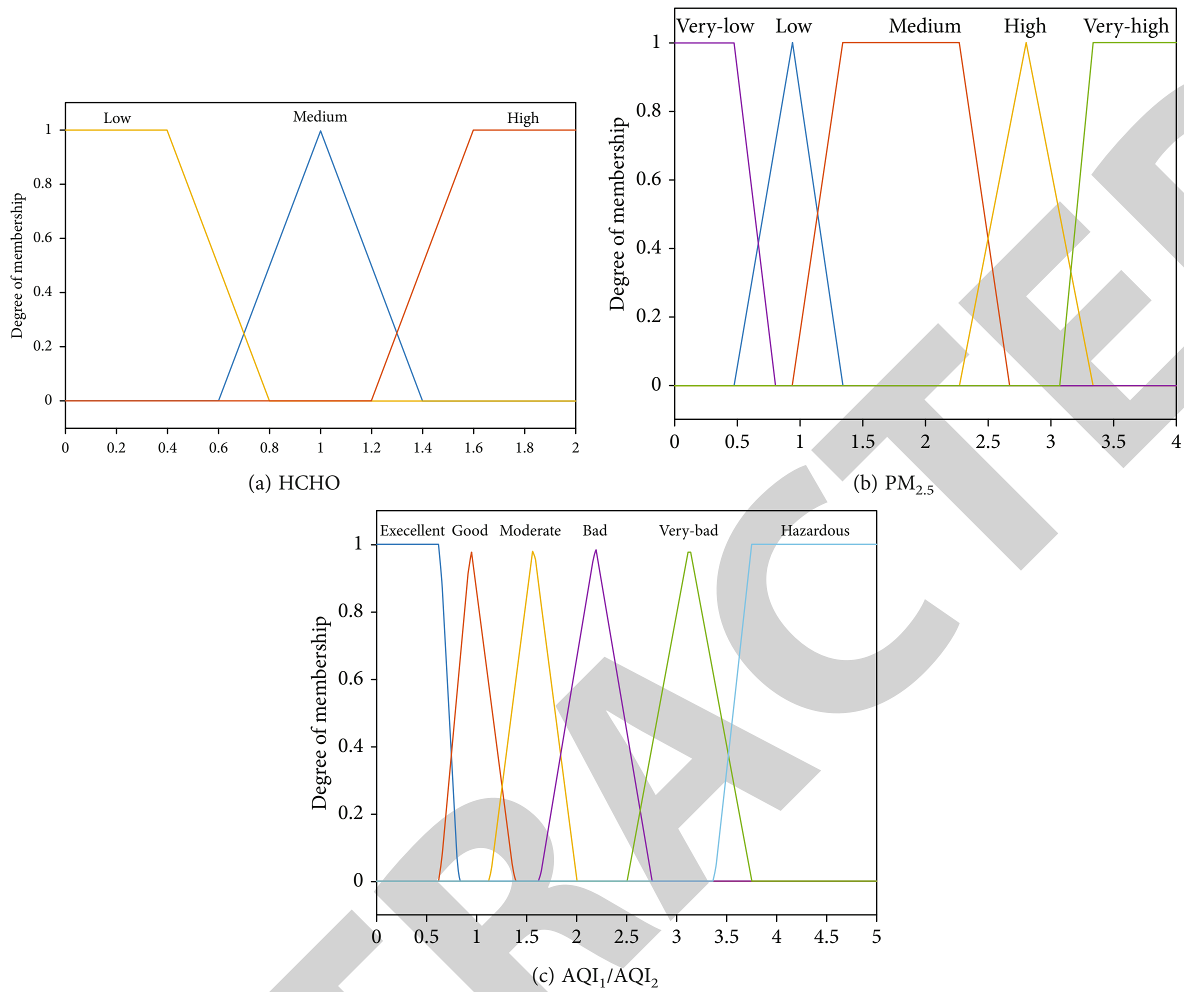

FIGURE 3: Membership functions and universe of fuzzy input/output.

obtained by weighted average of AQI_1 and AQI_2, that is,

$$FAQI = K_1 \times AQI_1 + K_2 \times AQI_2, \quad (1)$$

where $AQI_1 = f_1(CO_2, VOC, HCHO)$ and $AQI_2 = f_2(PM_{2.5}, PM_{10})$ represent the fuzzy air quality index of air pollutants and inhalable particulate matters, respectively, K_1 and K_2 are their weight coefficients, and FAQI is the overall fuzzy evaluation result.

3.1.1. Transformation of Input/Output Ranges. Actual input/output should be converted into fuzzy input/output by means of scale transformation [28–30]. Assume that x is the actual input/output and its range is $[x_{min}, x_{max}]$, if the corresponding fuzzy input/output range is $[X_{min}, X_{max}]$, then the fuzzy input/output X can be calculated by

$$X = \frac{X_{min} + X_{max}}{2} + \frac{X_{max} - X_{min}}{x_{max} - x_{min}} \times \left(x - \frac{x_{min} + x_{max}}{2}\right), \quad (2)$$

where $X \in [X_{min}, X_{max}]$ and $x \in [x_{min}, x_{max}]$.

According to "Indoor Air Quality Standard (China)" (GB/T 18883-2002), the value range of the abovementioned five input indicators (measured air parameters) and two output evaluation indicators (air quality index) are given, as shown in Table 1.

By using formula (1), five kinds of actual input (HCHO, CO_2, VOC, $PM_{2.5}$, and PM_{10}) and two kinds of actual output (AQI_1 and AQI_2) can be translated into fuzzy variables, that is, HCHO, CO_2, VOC, $PM_{2.5}$, PM_{10}, AQI_1, and AQI_2, respectively.

3.1.2. Fuzzy Language and Membership Functions. Fuzzy languages to describe HCHO are defined as low, medium, and high, that is, $\{L, M, H\}$, with universe $\{0, 1, 2\}$. Z-shaped, triangle, and S-shaped membership functions (MF) are used to represent L, M, and H, respectively, as shown in Figure 3(a).

Fuzzy languages to represent CO_2, VOC, $PM_{2.5}$, and PM_{10} are defined as very low, low, medium, high, and very high, that is, $\{VL, L, M, H, VH\}$. The corresponding universe of these input variables is all $\{0, 1, 2, 3, 4\}$, and their membership function curves are similar. The membership function curve of $PM_{2.5}$, as a representative example, is shown in Figure 3(b).

Fuzzy languages to describe AQI_1 and AQI_2 are defined as excellent, good, moderate, bad, very bad, and hazardous,

Table 2: Fuzzy logic rules for FIS_1.

AQI_1		HCHO = *L*					HCHO = *M*					HCHO = *H*				
		VOC					VOC					VOC				
		VL	*L*	*M*	*H*	VH	VL	*L*	*M*	*H*	VH	VL	*L*	*M*	*H*	VH
	VL	*E*[1]	*E*	*G*[2]	*G*	*M*[3]	*G*	*M*	*M*	*B*[4]	*B*	*M*	*B*	*B*	VB	VB
	L	*E*	*G*	*G*	*M*	*M*	*M*	*M*	*B*	*B*	VB	*B*	*B*	VB	VB	VB
CO_2	*M*	*G*	*G*	*M*	*M*	*B*	*M*	*M*	*B*	*B*	VB	*B*	VB	VB	*VB*	*H*
	H	*G*	*M*	*M*	*B*	*B*	*M*	*B*	VB	VB	VB	*B*	VB	VB	*H*	*H*
	VH	*M*	*M*	*B*	*B*	VB	*B*	VB	VB	VB	*H*	*VB*	VB	*H*	*H*	*H*

[1]If HCHO is *L* (low), CO_2 is VL (very low), and VOC is VL (very low), then AQI_1 is *E* (excellent). [2]If HCHO is *L* (low), CO_2 is VL (very low), and VOC is *M* (medium), then AQI_1 is *G* (good). [3]If HCHO is *L* (low), CO_2 is VL (very low), and VOC is VH (very high), then AQI_1 is *M* (moderate). [4]If HCHO is *M* (medium), CO_2 is VL (very low), and VOC is *H* (high), then AQI_1 is *B* (bad).

that is $\{E, G, M, B, \mathrm{VB}, H\}$, and their membership function curves are shown in Figure 3(c).

3.1.3. Fuzzy Logic Rules and Fuzzy Inference. Fuzzy logic rules between the input and output variables greatly affect the performance of the FIS. Therefore, the designed logic rules must be complete and inconsistent rules must be avoided. Based on experts' knowledge and practical experience, two fuzzy logic rule tables are established for FIS_1 and FIS_2; one describes the relationship between HCHO, C O_2, VOC, and AQI_1 (shown in Table 2), and another describes the relationship between $PM_{2.5}$, PM_{10}, and AQI_2 (shown in Table 3).

Then, we take the calculation of AQI_1 as an example to illustrate how FIS_1 works. The input variables of FIS_1 are $HCHO(H)$, $CO_2(C)$, and $VOC(V)$, and the output variable of FIS_1 is $AQI_1(A^1)$. The total number of logic rules in FIS_1 is 75 ($3 \times 5 \times 5$) because HCHO, CO_2, and VOC have three, five, and five linguistic levels, respectively. And the fuzzy relationship R_i between the input and output variables of FIS_1 can be expressed as

$$R_i = \left[H_j \times C_m \times V_n\right]^{D_1} \times A_k^1, \tag{3}$$

where H_i, C_m, V_n, and A_k^1 are linguistic levels of H, C, V, and A^1, respectively; $i = 0, 1, 2, \cdots, 74$; $j = 0, 1, 2$; $m = n = 0, 1, 2, 3, 4$; $k = 0, 1, 2, 3, 4, 5$; D_1 is the dimension of matrix $[H_j \times C_m \times V_n]$.

Through union operation of R_i, we can obtain a fuzzy relationship matrix consists of 75 fuzzy relationships, as follows:

$$R = \bigcup_{i=0}^{74} R_i. \tag{4}$$

Finally, the air quality assessment result $AQI_1(A^1)$ can be calculated by

$$A^1 = [H \times C \times V]^{D_2} \times R, \tag{5}$$

where D_2 is the dimension of matrix $[H \times C \times V]$.

3.1.4. Fuzzy Decision Surface. Applying centroid defuzzification approach, for each input pair (HCHO, CO_2 and VOC),

Table 3: Fuzzy logic rules for FIS_2.

AQI_2		PM_{10}				
		VL	*L*	*M*	*H*	VH
	VL	*E*[1]	*G*[2]	*G*	*M*	*M*
	L	*G*	*M*	*M*	*M*	*B*
$PM_{2.5}$	*M*	*M*	*B*	*B*	*B*	VB
	H	*B*	VB	VB	VB	*H*
	VH	VB	VB	*H*	*H*	*H*

[1]If $PM_{2.5}$ is VL (very low) and PM_{10} is VL (very low), then AQI_2 is *E* (excellent). [2]If $PM_{2.5}$ is VL (very low) and PM_{10} is *L* (low), then AQI_2 is *G* (good).

the corresponding output (AQI_1) is computed by formula (4). Repeating this process, we can obtain an output surface, called fuzzy decision surface. When VOC is fixed, the fuzzy decision surface of FIS_1 is shown in Figure 4. It can be seen from Figure 4 that if CO_2 is very high (belongs to interval [3, 4]) and HCHO is high (belongs to interval [1.5, 2]), then the estimated AQI_1 is around 4.2 (see yellow area), meaning that air quality is hazardous.

Similarly, we can also get the fuzzy decision surface of FIS_2, as shown in Figure 5. It can be found from Figure 5 that AQI_2 is positively correlated with both $PM_{2.5}$ and P M_{10}. However, when $PM_{2.5}$ is very high (belongs to interval [3, 4]), even if PM_{10} is very low (belongs to interval [0, 1]), the calculated AQI_2 value is still more than 3, implying that the considered air environment is assessed as very bad.

3.2. Design of SACM Mechanism. In order to realize automatic and reasonable regulation of IAQ, we design a simple adaptive control mechanism, called SACM, to adaptively and automatically control the working status of IAQMCS system according to real-time FAQI value, which ensures good quality of indoor air.

Assume that the ventilation system (VS) bought from market has rated power $P_e^{vs} = 100$ W, then we can obtain its actual power P_r^{vs} by

$$P_r^{vs} = u \times P_e^{vs} = u \times 100\mathrm{W}, \tag{6}$$

where u is the output of SACM.

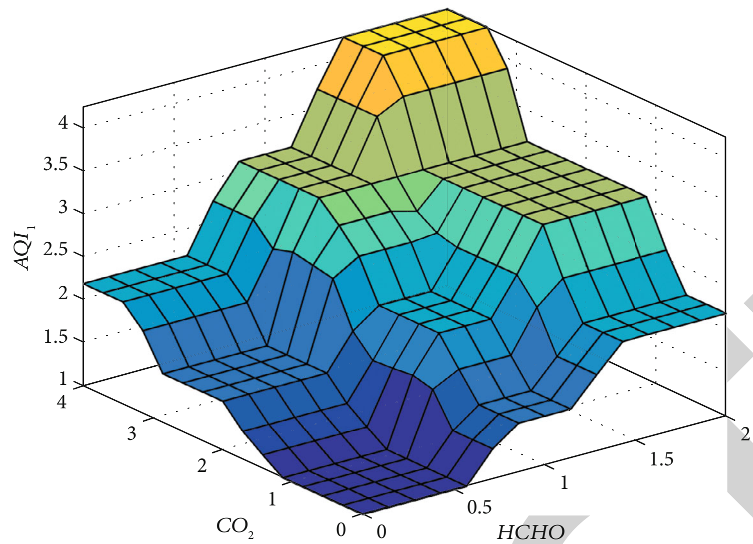

Figure 4: Fuzzy decision surface of FIS_1 when VOC is fixed.

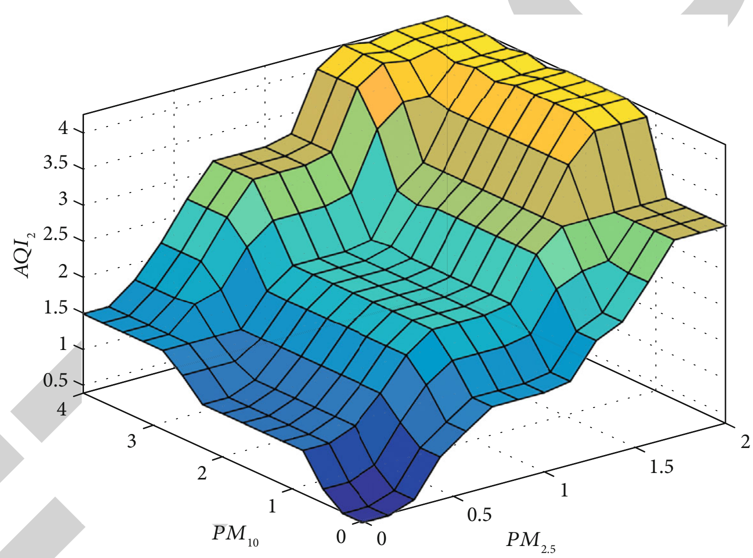

Figure 5: Fuzzy decision surface of FIS_2.

Generally, existing VS on the market has four tap positions: shutdown (0 W), low speed (30 W), medium speed (60 W), and high speed (100 W). Therefore, u is set to 0, 0.3, 0.6, and 1.0, respectively, corresponding to above four tap positions one by one.

The opening or closing status of doors and windows will affect the operation effect of the VS. For example, when haze weather occurs, if the doors and windows are open, no matter how the VS works, the indoor $PM_{2.5}$ concentration will exceed standard level. In order to avoid the impact of outdoor air pollution on indoor air environment, we assume that doors and windows are closed throughout, and design six adaptive control rules between input FAQI and output u, as follows:

(i) Rule 1: if $0 \leq \text{FAQI} \leq 50$ (excellent), then $u = 0$ (shutdown)

(ii) Rule 2: if $50 < \text{FAQI} \leq 100$ (good), then $u = 0.3$ (low speed)

(iii) Rule 3: if $100 < \text{FAQI} \leq 150$ (lightly polluted), then $u = 0.3$ (low speed)

(iv) Rule 4: if $150 < \text{FAQI} \leq 200$ (moderately polluted), then $u = 0.6$ (medium speed)

(v) Rule 5: if $200 < \text{FAQI} \leq 300$ (heavily polluted), then $u = 1.0$ (high speed)

(vi) Rule 6: if $\text{FAQI} > 300$ (severely polluted), then $u = 1.0$ (high speed).

It is not difficult to understand above control rules. When FAQI belongs to different AQI intervals [31], reflecting that the comprehensive quality of indoor air has reached

Table 4: Simulink simulation parameters.

Parameter	Value
Room volume	$147 m^3$ ($7 m \times 7 m \times 3 m$)
Removal rate of $PM_{2.5}/PM_{10}$	0.2/0.1
Indoor source strength of $PM_{2.5}/PM_{10}$	$0\ \mu g/(m^3 \cdot h)$
Indoor source strength of CO_2, VOC, HCHO	$0.015\ m^3/(h \cdot person)$, $0.025\ mg/(m^3 \cdot h)$, $0.005\ mg/(m^3 \cdot h)$
Ambient air flow	$200\ m^3/h$
Recirculated air flow	$100\ m^3/h$
Penetration factor for $PM_{2.5}/PM_{10}$	0.68/0.7
Initial indoor concentration of CO_2, VOC, HCHO	500 ppm, $0.2\ mg/m^3$, $0.01\ mg/m^3$
Initial indoor concentration of $PM_{2.5}/PM_{10}$	$124.62/134.02\ \mu g/m^3$
Simulation time	48 h (2 days)

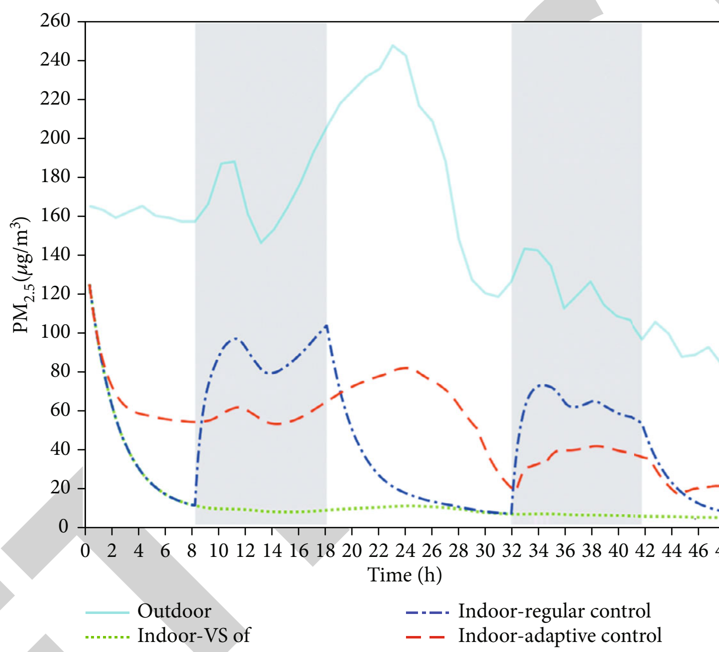

Figure 6: Curve of indoor $PM_{2.5}$ concentration under three schemes.

different pollution levels. Hence, adaptive controller should dynamically regulate the working state of the VS according to the real-time indoor air pollution level.

4. Simulation and Experimental Analysis

In this section, in order to evaluate the performance of the proposed FAQI model and SACM mechanism, theoretical simulations are first performed under MATLAB/Simulink. Then, our proposal is implemented into the proposed IAQMCS system, and some practical experiments are performed. During actual tests, two school offices, equipped with IAQMCS system, are considered experimental subjects, one using SACM, while another using traditional time-based control method.

4.1. Simulation Results and Analysis. Inspired by literature [32, 33], we construct an office air quality Simulink model, consisting of 6 air metrics: $PM_{2.5}$, PM_{10}, HCHO, VOC, CO_2, and FAQI. Simulation experiments are performed under three different scenarios: (1) the ventilation system is off (VS off), (2) the VS is under regular control method (turn on the VS at 8 am and turn off the VS at 6 pm), and (3) the VS is under the proposed adaptive control strategy. Simulink simulation parameters are summarized in Table 4.

4.1.1. $PM_{2.5}$ and PM_{10}. Figure 6 shows the curve of indoor $PM_{2.5}$ concentration under three schemes. Please note that the outdoor $PM_{2.5}$ data come from “Moji Weather” website [34] and that the time of interest (ToI) is office time (from 8 am to 6 pm, see gray area in Figure 6).

It can be seen from Figure 6 that during office hours, if the VS is off, the concentration of indoor $PM_{2.5}$ will be the lowest. This is because when we turn off the VS, the ambient air flow from outdoor is greatly reduced, preventing outdoor $PM_{2.5}$ entering indoors. However, compared with regular control, the proposed adaptive control can lower the level of indoor $PM_{2.5}$ within ToI. Please note that the curve of

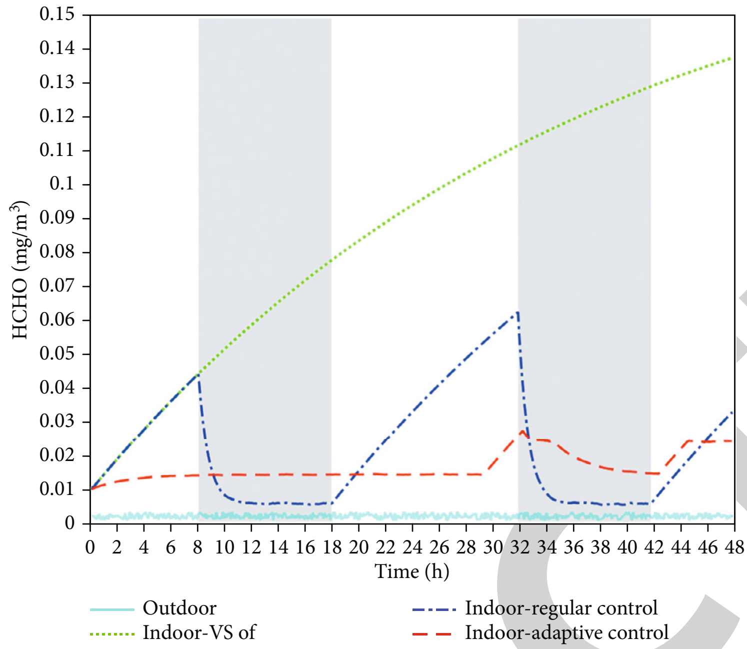

Figure 7: Curve of indoor HCHO concentration under three schemes.

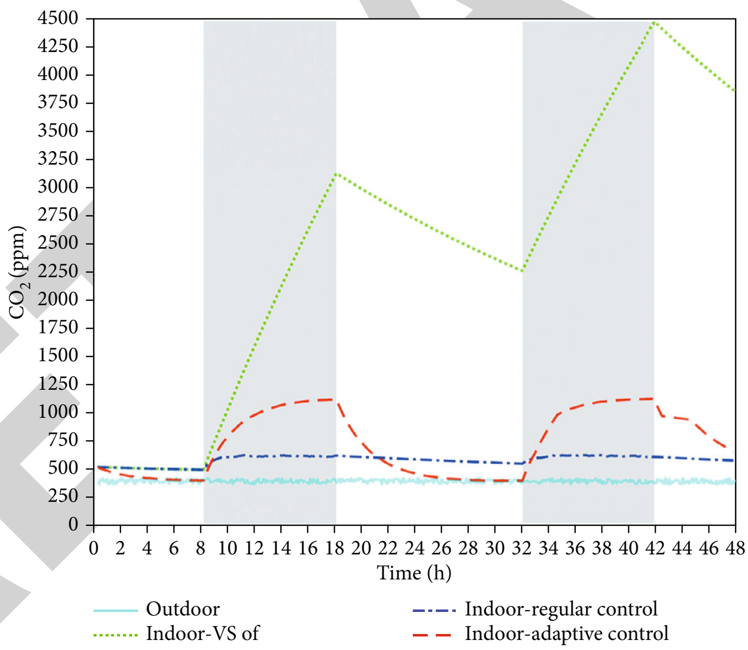

Figure 8: Curve of indoor CO_2 concentration under three schemes.

indoor PM_{10} concentration under different schemes is similar to that of indoor $PM_{2.5}$, due to page limitations, further discussion is not given.

4.1.2. HCHO, VOC, and CO_2. Figure 7 shows the curve of indoor HCHO concentration under three scenarios. We can see from Figure 7 that when the VS if off, the indoor HCHO concentration will become higher and higher, due to lack of ventilation. However, during ToI, indoor HCHO concentration under adaptive control is around 0.01 mg/m^3, while that under regular control is around 0.005 mg/m^3. The reason is that adaptive control considers the balance issue of various air parameters, in order to suppress the increase of indoor $PM_{2.5}$ and PM_{10} levels, ventilation rate is not set very high, resulting in slightly higher indoor HCHO concentration.

Regarding performance metric VOC, the change trend of its concentration is similar to that of HCHO concentration. Under adaptive control, indoor VOC concentration during working hours is around 0.1 mg/m^3, which is much lower

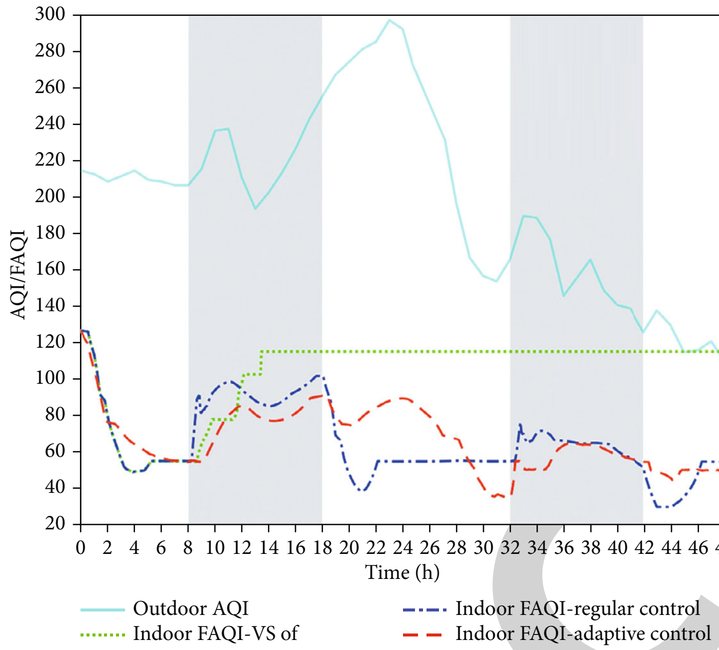

Figure 9: Curve of outdoor AQI and indoor FAQI.

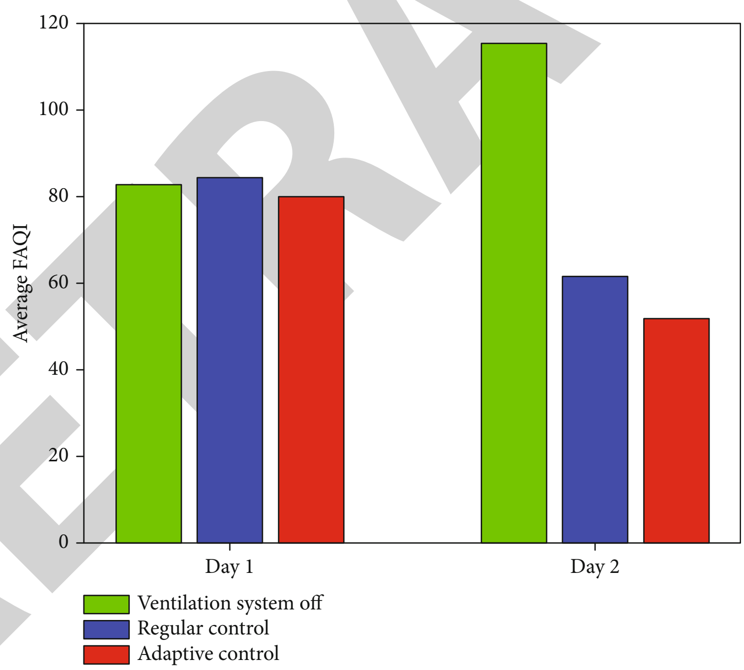

Figure 10: Comparison of average FAQI under three schemes.

than the upper limit value (0.8 mg/m^3) given by Chinese national standard. Hence, people who work indoors will not feel uncomfortable.

Figure 8 shows the curve of indoor CO_2 concentration under three schemes. It can be found that indoor CO_2 concentration under "VS off" increases dramatically within ToI but drops a lot during non-ToI. Because people stay in the office during working hours and produce a large amount of CO_2 through breathing, when they leave the office after work, indoor CO_2 concentration will gradually decrease. Compared with regular control, the proposed adaptive control brings higher CO_2 concentration, but its maximum just slightly exceeds the national standard limitation value (1000 ppm). Hence, it is acceptable to tolerate a little bit higher CO_2 concentration without suffering from symptoms like dizziness and chest tightness.

Figure 11: IoT prototype of IAQMCS system.

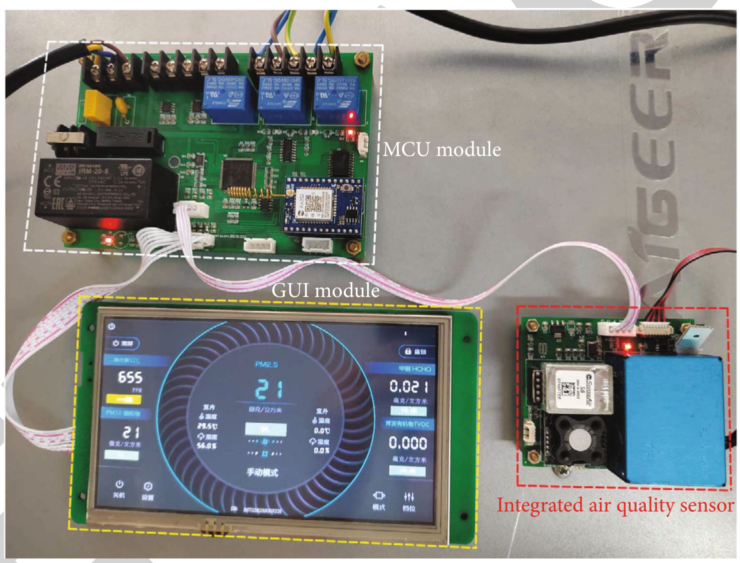

Figure 12: Prototype of air quality sensing system.

4.1.3. Outdoor AQI versus Indoor FAQI. The curve of outdoor AQI and indoor FAQI is shown in Figure 9. Note that outdoor AQI data are from [34] and calculated by traditional method, while indoor FAQI data are from the designed IAQMCS system and computed by the proposed FAQI model. Due to serious air pollution, the outdoor AQI is relatively high during 48 h experiment time. As for indoor FAQI, we can see from Figure 9 that the proposed adaptive control performs better than other methods within ToI. By simultaneously taking into account 5 kinds of air parameters ($PM_{2.5}$, PM_{10}, HCHO, VOC, CO_2), the proposed method avoids the problem of imbalanced concentration of these parameters and reduces comprehensive FAQI value, thus improving overall IAQ level.

Furthermore, we compare the average FAQI under three schemes, as shown in Figure 10. It can be found from Figure 10 that the average FAQI of three schemes in ToI of day 1 (8-18 h) differs a little (their FAQI value is all around 80). However, in ToI of Day 2 (32-42 h), the difference among average FAQI under three control methods is significant. Exactly, the average FAQI of VS-off, regular control and adaptive control is about 115, 61, and 52, respectively. That is to say, compared with conventional regular control, the proposed adaptive control can decrease average FAQI by 14.75% and improve IAQ from “good” to nearly “excellent.”

4.2. Experimental Results and Analysis. In order to further evaluate the practical performance of our proposal, the IoT

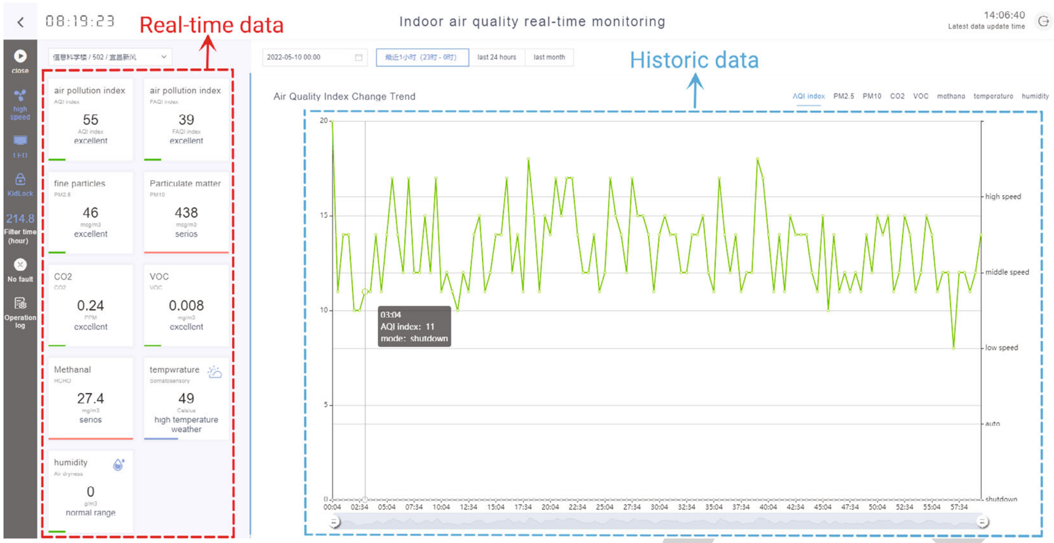

Figure 13: Web GUI of IAQMCS system.

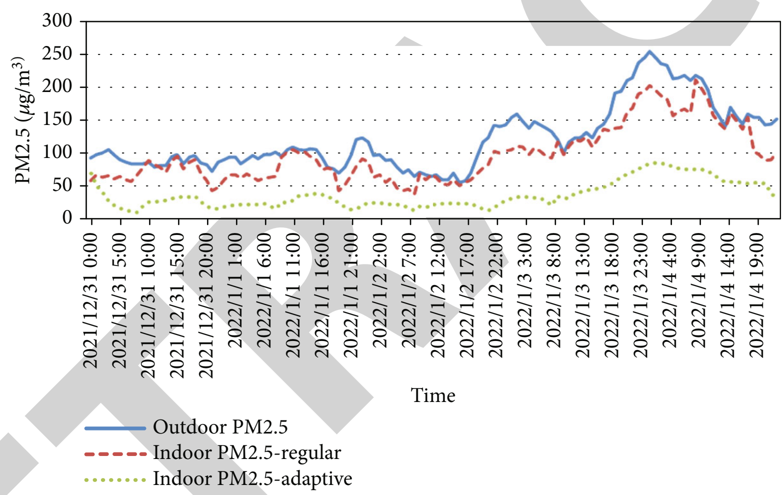

Figure 14: Measured outdoor and indoor $PM_{2.5}$ concentrations during 31 December 2021 to 4 January 2022.

prototype of IAQMCS system is designed and implemented in a 7 m × 7 m × 3 m office, as shown in Figure 11.

We can see from Figure 11 that IAQMCS system consists of a ventilation system (see red box), an air quality sensing system (see yellow box), and 4 air exchange holes (see green marks). And the air quality sensing system is made up of an integrated air quality sensor (see red box), a MCU module (see white box), and a GUI module (see yellow box), as shown in Figure 12.

The integrated air quality sensor includes CO_2 sensor, VOC sensor, HCHO sensor, PM sensor, and Temp-humi sensor. The MCU module contains STM32 embedded system, 4G wireless communication unit, electric relay, etc. The GUI module is responsible for displaying real-time air pollutants data on the screen and transferring users' operation commands to STM32 embedded system, which realizes friendly human-machine interaction.

Figure 13 shows the Web GUI of IAQMCS system. Remote users can view real-time IAQ data and set up the working mode of the VS. They can also track historic IAQ data and check other device information such as child lock status, filter time, and operation log.

In order to explore the practicability of the proposed IAQMCS system, FAQI model, and SACM mechanism, comparative experiments were performed during 31 December 2021 to 4 January 2022. After experiments, we extract historic data of various air parameters from database, as shown in Figures 14–17.

Figure 14 depicts the measured outdoor and indoor $PM_{2.5}$ concentrations during 31 December 2021 to 4 January 2022. Obviously, indoor $PM_{2.5}$ concentration is lower than outdoor one. However, compared with regular control, the proposed adaptive control (SACM) significantly decreases indoor $PM_{2.5}$ concentration.

Figure 15 presents the measured outdoor and indoor CO_2 concentrations during 31 December 2021 to 4 January 2022. We can see from Figure 15 that indoor CO_2 concentration is evidently higher than outdoors, owing to the

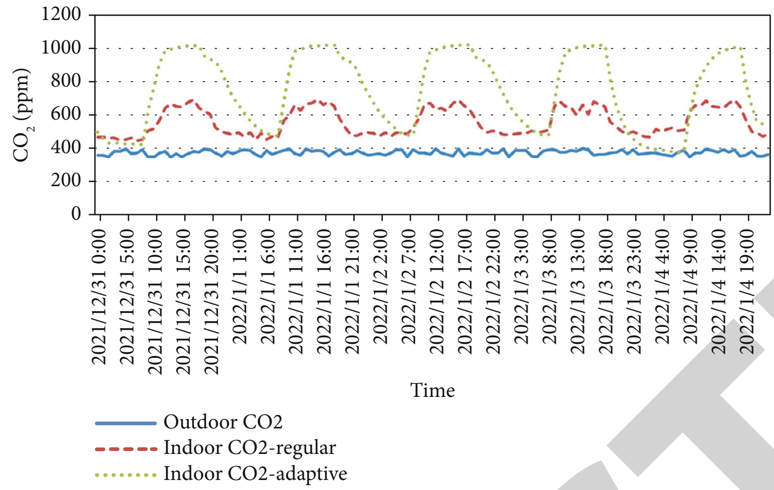

FIGURE 15: Measured outdoor and indoor CO_2 concentrations during 31 December 2021 to 4 January 2022.

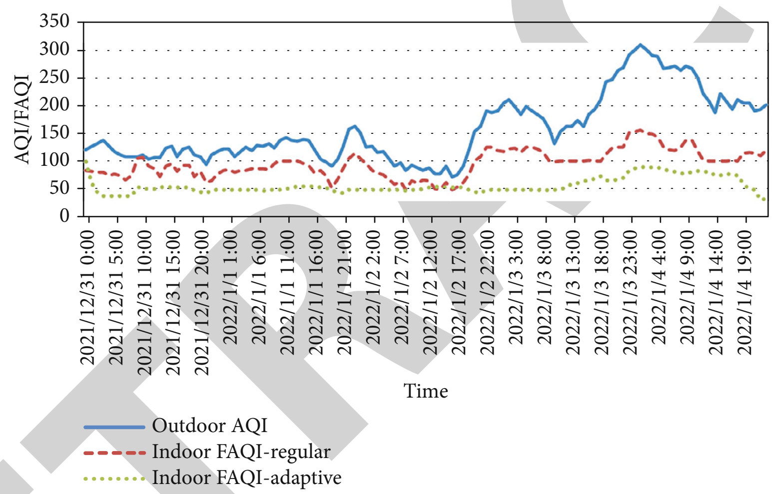

FIGURE 16: Official outdoor AQI and the calculated indoor FAQI during 31 December 2021 to 4 January 2022.

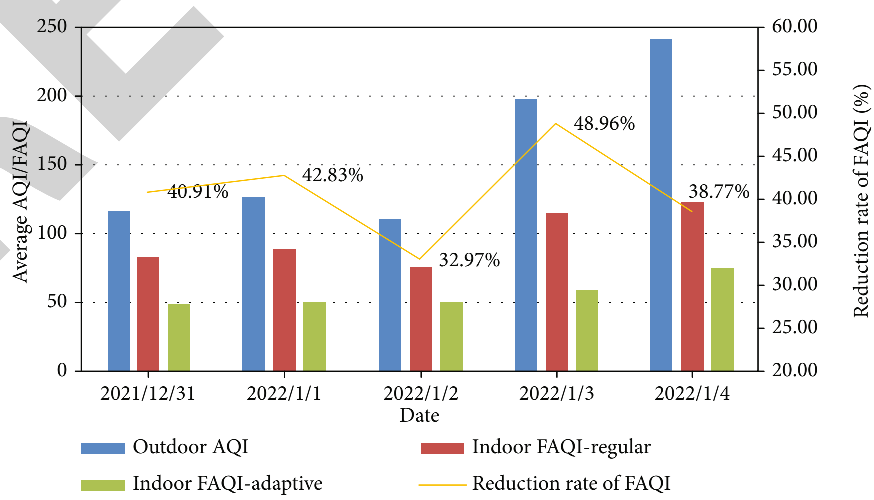

FIGURE 17: Comparison of average daily FAQI under regular control and adaptive control.

respiration of office occupants. Nevertheless, during most of the experimental time, the indoor CO_2 concentration under adaptive control is higher than that under regular control. It is easy to understand this fact, in order to restrain outdoor $PM_{2.5}/PM_{10}$ from penetrating indoors, the ventilation rate of the VS is appropriately reduced, resulting in a rise of CO_2 level. However, the sacrifice of CO_2 is worthy, because rising CO_2 to a bearable level (1000 ppm) can solve the imbalance of various air parameters, thus improving the comprehensive level of IAQ.

Figure 16 shows the official outdoor AQI and the calculated indoor FAQI during 31 December 2021 to 4 January 2022. We can find from Figure 16 that indoor FAQI (using regular or adaptive control) is lower than outdoor AQI, implying that indoor air environment is better and more desirable than outdoors. However, compared with regular control, the proposed adaptive control can further reduce indoor FAQI and improve overall IAQ level.

In order to further analyze the improvement of FAQI after using our proposal, we compare the average daily FAQI under regular control and adaptive control, as shown in Figure 17. It can be clearly seen from Figure 17 that the average daily FAQI under the proposed adaptive control (see green columns) declines significantly, compared with that under regular control (see red columns). Moreover, the reduction rate of FAQI ranges from 32.97% to 48.96%, with mean value reaching 40.89%.

Based on above analysis, we can believe that our proposal not only stably monitors real-time/historic indoor air environment but also adaptively control the VS to lower the FAQI value and improve overall IAQ. It is worth pointing out that the production cost of the whole system is only 5000 RMB (around 746.5 dollars), which achieves efficient monitoring, assessment, and control of IAQ with low cost.

5. Conclusion

In this paper, we propose a method to achieve efficient monitoring and adaptive control of indoor air environment. Firstly, the IoT architecture of an indoor air quality monitoring and control system (IAQMCS) is designed. Based on fuzzy control theory, a fuzzy air quality index (FAQI) model and a simple adaptive control mechanism (SACM) are proposed to realize the accurate evaluation and reasonable control of indoor air. Theoretical simulations and practical experiments are performed, respectively. The experimental results demonstrate that the proposed method reduces average daily FAQI by 40.89% and improves overall IAQ level.

The next step of our work is to perform long-term experiments to further verify the stability and effectiveness of the proposed method. And deep learning will be adopted to optimize the system, so as to predict future IAQ and provide suitable measures for users in advance.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there is no conflict of interest.

Acknowledgments

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