Development of air quality monitor

ABSTRACT :

Many air pollutants are inhaled by human breathing, increasing the prevalence of respi- ratory disease and even mortality. With the recent COVID-19 issue, the number of air pollutants affecting humans is demands further investigation. However, there are not many adequate air mea- suring devices that can cover a variety of air pollutants. In this study, the developed air measurement system is able to measure sixteen air pollutants (PM_{10}, $PM_{2.5}$, $PM_{4.0}$, $PM_{1.0}$, CO_2, CH_4, temperature, humidity, VOCs, O_2, H_2S, NH_3, SO_2, CO, O_3, NO_2) in real time. The developed 'multi-item air quality monitoring system' can measure sixteen air pollutants in real time and transmit them to the server and the smartphone application at the same time. It was developed to reduce air pollu- tant damage to humans by emergency alerts using the smartphone application. The development system is composed of hardware development (measurement device) and software development (smartphone application, server). To verify the reliability of the developed equipment, a comparative test, temperature–humidity accuracy test, and operating temperature test were conducted. In the comparative test, difference ratios of ±5% for PM_{10}, ±6% for $PM_{2.5}$, ±4% for O_3, ±5% for NO_2, ±7% for CO, and ±7% for SO_2 were found compared to the professional measuring devices. The temperature and humidity accuracy test result showed high reliability at ±1% and humidity ± 2%. The result of the operating temperature test showed that there was no problem in normal operation, However, further tests including the long-term comparative test and the closed chamber test will be carried out for all sensors. Additional work including a long-term test for more clear reliability of the device and closed chamber accuracy test for all 16-item sensors, data acquisition rate, and data transmit rate are in progress for commercializing the device.

INT***RODUCTION :***

The risks posed by air pollution lead to side effects such as poor public health and increased mortality [1]. According to the World Health Organization (WHO), 4.2 million people die each year from outdoor air pollution and 3.8 million people die from indoor air pollution [2]. The premature mortality rate from air pollution is expected to double by 2050, which is recognized as the world's most serious environmental and health threat [3]. Particles smaller than 2.5 μm are called ultra-particulate matter, which float in the air and can be easily inhaled by humans. They affect premature death and may travel interconti- nentally, affecting air quality and public health [4]. Bourdrel et al. (2021) reported that air pollution affects chronic disease and may be associated with increased mortality associated with COVID-19, and that exposure to air pollution reduces immune responses, promoting virus penetration and replication [5].The size of the dust particles varies from a few nanometers to several tens of mi- crometers; however, generally, in the literature, the first particles are less than 2.5 μm, the second particles are between 2.5 μm to 10 μm, and the third particles are up to 100 μm [6]. Kelly et al. (2012) reported the toxicity of particulate matter (PM), as they penetrate the alveoli and bronchi and are deposited mainly in the bronchi and are filtered by the phar- ynx [7]. Stanaway et al. (2018) reported that the exposure to particulate matter less than 2.5 μm in diameter decreased the world average life span in 2016 by more than 1 year [8]. Particles less than 1.0 μm in diameter negatively affect the air–blood barrier near the lungs and cause illnesses such as stroke, lung cancer, chronic obstructive pulmonary disease, and respiratory infections [9]. Rizzato et al. (2020) concluded that particulate matter can have a devastating effect on vulnerable groups, including the elderly, pregnant women, and children, and it appears that it is closely related to mortality [9].

Combustion gases such as gaseous carbon monoxide, carbon dioxide, NOx, SO_2, and volatile organic compounds negatively affect the air quality and the human living environment [10]. Carbon monoxide is a product of the incomplete combustion of fossil fuels and causes poisoning [11]. Carbon dioxide exists in a relatively high concentration in the air and is used for the human body such as in carbonated drinks and fire extinguishers, but it is also a product of fossil fuel combustion and is a substance that absorbs infrared rays and causes a greenhouse effect [12]. Nitrogen oxides are generated by the combustion of fossil fuels in engines and industrial processes, and NO_2 is toxic and may cause lung- related health deterioration [13]. Sulfur dioxide mainly occurs in industrial activities and not only irritates the airways but also affects acid rain [1]. As hazardous chemicals such as volatile organic compounds, propanol, and toluene, they exhibit high vapor pressure at room temperature and can be dispersed in certain concentrations in the air, causing air pollution [14]. Methane is colorless, odorless, and non-toxic, but at high concentrations, it causes the risk of asphyxiation and explosion due to oxygen depletion [9].

For this reason, real-time measurement and monitoring is very important to identify air quality problems. Suganya et al. (2021) developed an IOT-based air monitoring device that can measure O_3, SO_2, and CO [15]. Kim et al. (2014) developed a measuring instrument that can measure CO_2, VOCs, SO_2, NOx, CO, PM, and ozone to check indoor air quality in real time and developed factors that change indoor air quality (wind, location, airflow, density, and size) were investigated [16]. Sung and Hsiao (2021) developed an IOT smart air control system that is transmitted in real time through Wi-Fi using PM, CO, and CO_2 sensors [17]. Recently, many commercial air quality measuring devices have been released for real time air quality measurement [18,19]. Particle counters that measure particulate matter are developed in various ways from low-cost products to high-priced products [18,19]. Recently, not only particulate matter but also various types of air quality measuring devices such as particulate matter (PM), volatile organic compounds (VOCs), CO_2, temperature, and humidity have been released [20–27]. The low-cost multi-item device can measure PM, temperature, humidity, carbon dioxide, and total organic compounds and provides measured data to consumers through the IOT linkage function [20–23]. However, low-cost air quality measurements are not used for professional environmental measuring services due to issues with the accuracy and reliability of sensors. On the other hand, professional environmental measurements with high-precision sensors are rarely applied to IOT linkage, so they cannot provide real-time data to users [24,26]. Gas detectors widely used in the field rarely have IOT functions [26,27]. Professional environmental measuring equipment with good accuracy has many inconvenient factors such as a small number of items, lack of IOT function, and the inconvenience of measurement, size, and weight. To overcome these disadvantages, this study was developed with the three goals of expanding the measurement items, improving the accuracy of the measurement device, and increasing the convenience through a smartphone application and a server. To expand the measurement items, we developed a technology that can install a sensor capable of measuring 16 items with high precision in a small space. To improve the accuracy of the measuring device, a high-precision sensor was used, automatic and manual calibration of the sensor was enabled, and a constant current was developed to reduce the error of the sensor and achieve the optimal air flow. To increase convenience, a smartphone application was developed, and a server program was developed so that users could control and monitor from their smartphones and computers.

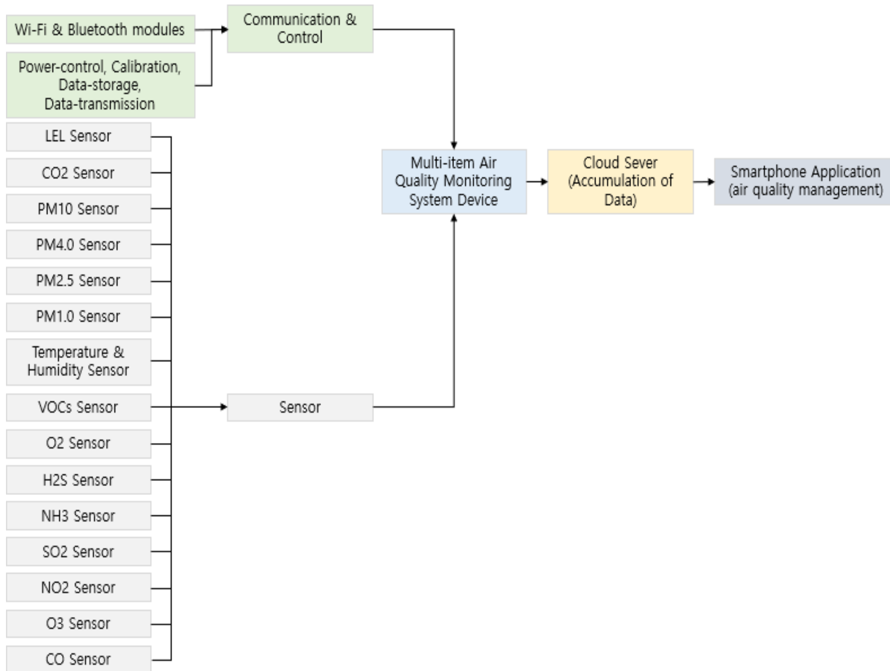
The developed device in this study consists of 16 air pollutant items including PM(PM10, PM4.0, PM2.5, PM1.0), carbon dioxide (CO_2), methane (CH_4), temperature, hu- midity, volatile organic compounds (VOCs), oxygen (O_2), hydrogen sulfide (H_2S), ammonia (NH_3), sulfur dioxide (SO_2), carbon monoxide (CO), ozone (O_3), and nitrogen dioxide (NO_2) can be measured in real time. The data of 16 measured items are transmitted to the server and the smartphone application through Bluetooth and Wi-Fi. Based on the transmitted data, it was developed to identify the concentration of air pollution. When the air pollution concentration is high, it is developed to warn of a risk to the user using an emergency alert

Materials and methods:

Process of Multi-Item Air Quality Monitoring System

A multi-item air quality monitoring system component consists of a hardware part and a software part. The hardware part consists of a sensor unit and a communication control unit. The sensor unit consists of a total of 16 items: PM10, PM2.5, PM4.0, PM1.0, CO_2, CH_4, temperature, humidity, VOCs, O_2, H_2S, NH_3, SO_2, NO_2, O_3, and CO. The total number of installed sensors are eleven. The communication unit consists of a Wi-Fi module and a Bluetooth module. The software part consists of a web program and a smartphone application. The measurement process is that the sensor unit of the hardware part measures 16 air pollution items, the measured data are transmitted to the cloud server through the communication unit, and the cloud service is transmitted to the smartphone application and the web program.

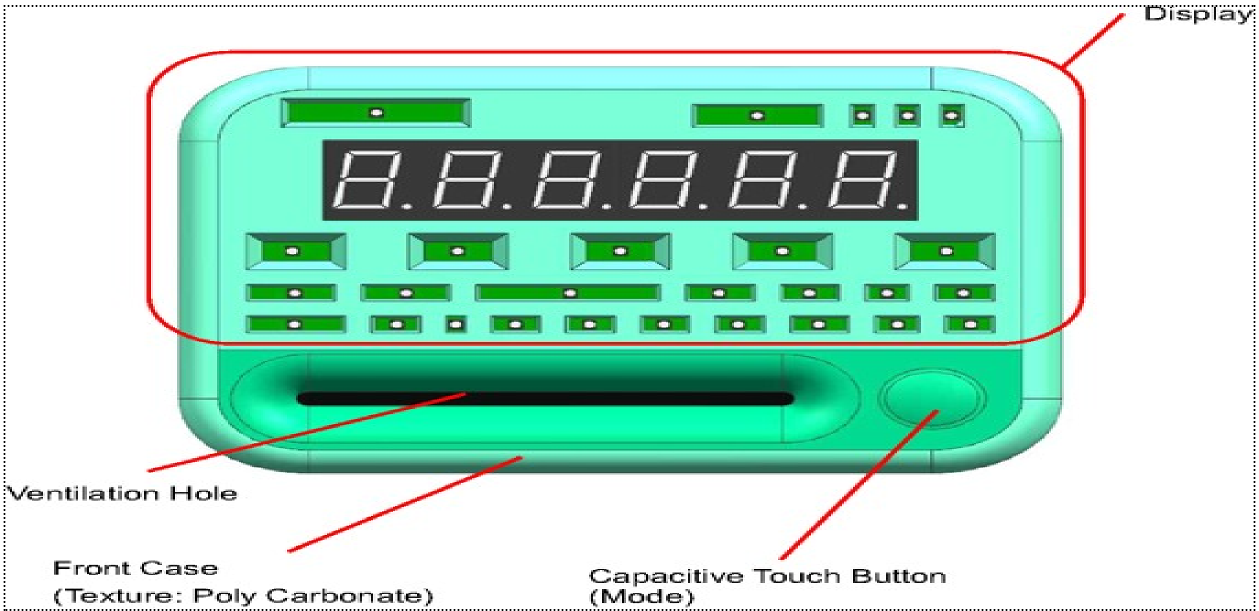
Measured data can be saved in USB memory and a server at the same time during air quality measurement. In the smartphone application and web program, real-time measurement data can be checked daily and monthly, and an emergency alert can be transmitted to the user when the air pollution level is high. These monitoring and alerting systems have been studied by many researchers. Feenstra et al. (2020) developed an open-source R package to meet data science needs of community air sensor networks [28]. The program allows users to access historical data, add spatial meta data, and create maps and plots for viewing community monitoring data [28]. Larkin et al. (2015) developed a smartphone software package for predicting air pollutant concentrations at mobile locations. They observed PM10 and PM2.5 [29]. Sung et al. (2019) developed a smart air quality monitoring system that measures the PM10, PM2.5, PM1.0, CO, CO_2, VOCs, temperature, and humidity. They connected the developed monitoring system to the smartphone application [30]. A schematic diagram of the developed multi-item air quality monitoring system is shown in fig



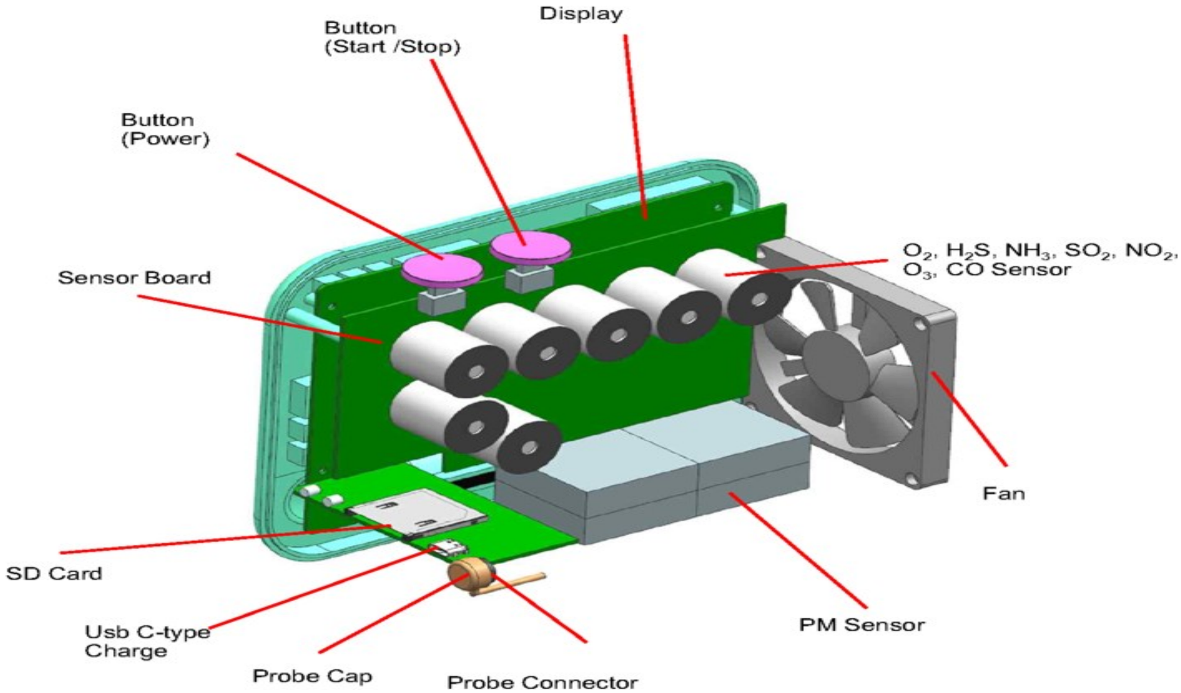
Hardware Process of Multi-Item Air Quality Monitoring System

The hardware part of the multi-item air quality monitoring system is divided into a sensor part and a communication part. The sensor unit includes nine sensors including a PM sensor, a temperature and humidity sensor, a VOC sensor, an oxygen sensor, a hydrogen sulfide sensor, an ammonia sensor, a sulfur dioxide sensor, a nitrogen dioxide sensor, an ozone sensor, and a carbon monoxide sensor. The carbon dioxide and methane sensors are attached to the separated probe rod and used in connection with the main device. Detailed sensor specifications can be found in Table 1. The PM sensor can measure the PM1.0, PM2.5, PM4.0, PM10 from 0 to 1000 µg/m3 in real time by a light scattering method. The carbon dioxide and methane sensor use the non-dispersive infrared absorption (NDIR) method, and the measurement range is 400 ppm to 10,000 ppm for carbon dioxide and 0 ppm to 50,000 ppm for methane. The oxygen sensor measures 0 to 25% oxygen electrochemically. The hydrogen sulfide sensor uses an electrochemical method, and the measurement range is 0 to 100 ppm. The ammonia sensor uses an electrochemical method, and the measurement range is 0 to 100 ppm. The sulfur dioxide sensor based on the electrochemical method can measure 0 to 20 ppm. Ozone can be measured from 0 to 20 ppm electrochemically. CO based on the electrochemical method can measure from 0 to 100%. The volatile organic compound sensor can measure 0 to 60,000 ppb in the electrochemical method. The temperature and humidity sensor measures the temperature from 40 ◦C to 125 ◦C and the humidity from 0% to 100%. The communication control unit is equipped with Bluetooth and Wi-Fi modules for short- and medium-range communication and a USB memory storage module for data storage. The Wi-Fi module has a communication distance of about 500 m or more in low power. For the Bluetooth module, Bluetooth 4.2 NRF52832 Module, which has been verified for commercialization, is used.

shows the external and internal design of the developed monitoring system. The exterior design is shown in Figure 2a. The material of the front case is made of hard polycarbonate. The display shows the measurement value, measurement item, time, operation status, and logo. The ventilation hole was installed to inhale PM and not interfere with other sensors. A capacitive touch button allows the measurement items displayed on the LED display to be changed by touching the button. The interior design is shown in Figure 2b. The main board is designed to make it easy to attach and replace sensors, to attach many sensors to a minimum area, and to avoid interference. The button part was installed by dividing it into a power button and an operation button. It is designed with an interval of 20 mm so that there is no interference between the display board and the main board. For adequate measurement, a fan was introduced to control the air flow. For the power supply, C-type was introduced to make it compatible with existing portable electronic products. The SD card slot was designed to store data on the SD card.



(a)

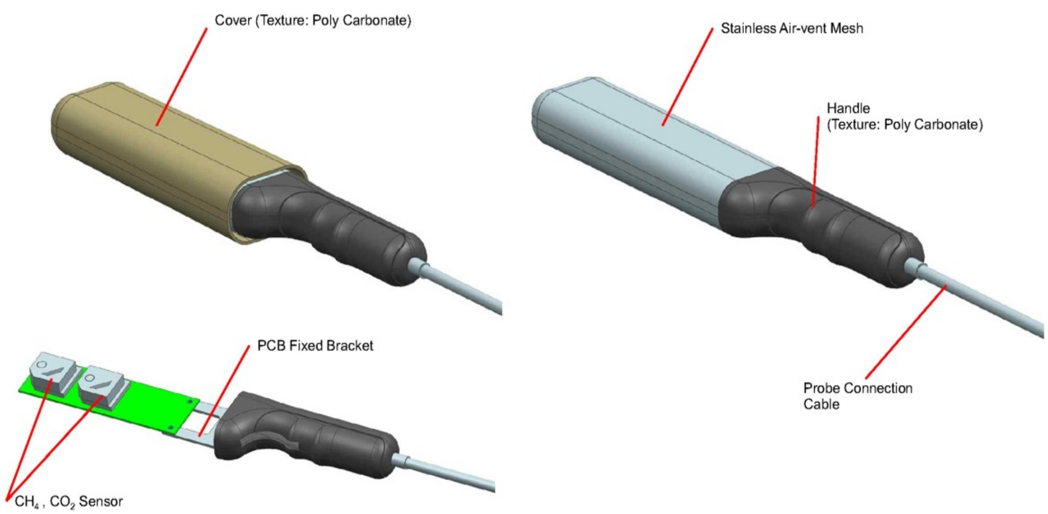


(b)

Hardware of (a) multi-item air quality monitoring system device front part; (b) rear part.

The methane sensor and carbon dioxide sensor were separately manufactured in the form of a probe rod so that they could be connected to the main device for measurement. A detailed picture is shown in Figure 3. The plastic used in the production was made of polycarbonate, which is a heat-resistant plastic. The measuring part is made of stainless steel and has a ventilation hole so that there is no problem in measurement, even in high heat.

The biggest advantage of the developed measuring device is that it can measure many items at once, and the number of measurement items can be adjusted according to the user’s needs through easy attachment and detachment of the sensor.

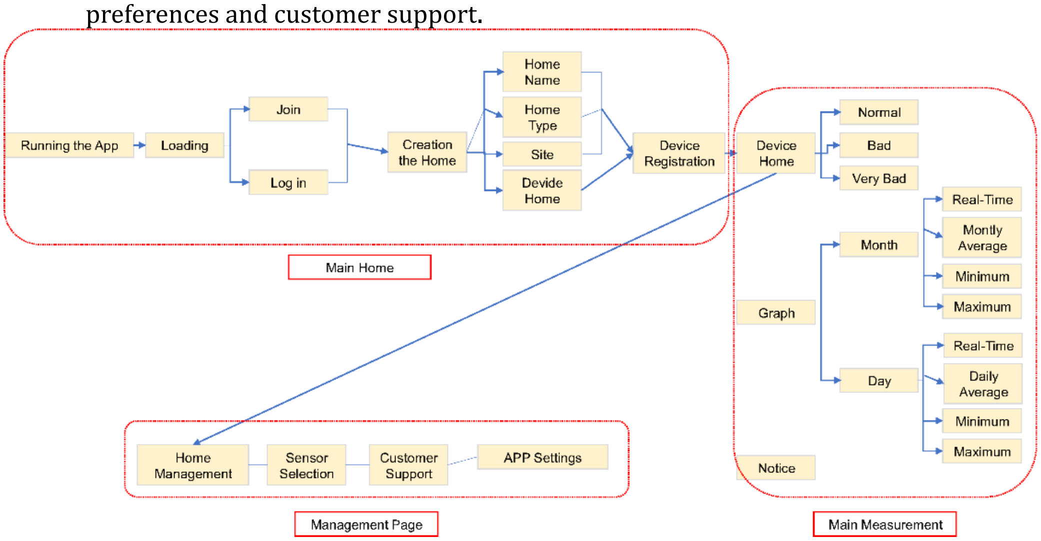


Hardware of air quality monitoring system (probe).

Software Process of Multi-Item Air Quality Monitoring System

In the software part, the data measured by the multi-item air quality monitoring system is stored in the server, and the stored data is transmitted to the user in real time through a smartphone application.

The structural diagram of the smartphone application is shown in Figure 4. The application diagram can be divided into three main parts: the main home part, the main measurement part, and the management part. To use the main home, the user needs to register as a member and can find out where the device is installed through the map function. After setting the location, the user can register their device to activate the main home. During this process, the wireless communication of the device is activated, and the measurement data is set up to be transmitted to the server. In the main measurement, the user can see the graph according to the measurement items, and the data can be viewed by month and day separately. The management page provides features that correspond to preferences and customer support.



Software (application) structure diagram.

Depending on the degree of pollution, the smartphone application can provide an alert notification for each pollutant source. The warning notification is delivered to the user according to the pollution level for each item in Table 2. The pollution level was applied with reference to the WHO Indoor Air Quality Guidelines [27]. The degree of contamination for the measurement items was expressed in three levels: normal, bad, and very bad. When each item changes to a bad level, a push notification pops up to inform the users about the current air quality. This function is developed to minimize damages to users due to polluted air environments. Jo et al. (2020) developed indoor air quality information by the device measuring the aerosols, VOC, CO, CO2, temperature, and humidity through web servers and applications. In addition, a quick alert system was introduced to minimize damage to the indoor air quality [31]. Peladarinos et al. (2021) developed an early warning system for COVID-19 infection using an air quality measurement system [32].

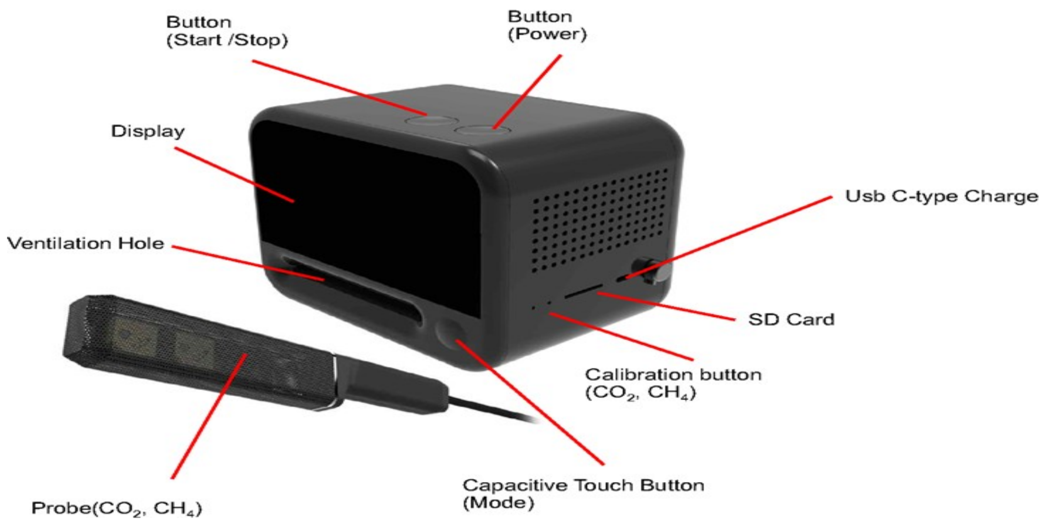
Index	Item	Unit	Normal	Bad	Very Bad	Risk
$PM_{2.5}$		μg/m^3	0~35	36~75	76~1000	Respiratory hazard
PM_{10}		μg/m^3	0~80	81~150	151~1000	Respiratory hazard
CO		ppm	0.0~9.0	9.1~15.0	15.1~1000	Poisoning
CO_2		ppm	0~1000	1001~3000	3001~10,000	Poisoning
VOCs		ppb	0~300	301~500	501~60,000	Poisoning
Measurement item	O_2	%	19.0~30.0	18.9 or less, 30.1 or more		Poisoning
	H_2S	ppm	0~5	6~100		Poisoning
	NH_3	ppm	0~5	6~40	41~100	Poisoning
	CH_4	ppm	0~140	141~50,000		Explosion Hazard
	SO_2	ppm	0.0~0.1	0.2~20.0		Poisoning
	NO_2	ppm	0.0~0.1	0.2~20.0		Poisoning
	O_3	ppm	0.0	0.1~0.15	0.16~20.0	Poisoning

Result and discussion:

According to the purpose of the multi-item air quality monitoring system, this section was produced by dividing the results into the hardware production result, the software production, and the reliability tests.

Hardware Fabrication of Multi-Item Air Quality Monitoring System

According to the hardware design of 2.2, a multi-atmospheric measuring device was manufactured, and the details are shown in Figure 5. O2, H2S, NH3, SO2, NO2, O3, and CO sensors are manufactured to fit into one board using the minimum area. The VOC sensor generates heat, so it was installed in a little gap. The temperature and humidity sensor were located next to the vent to avoid interference from the inside generated heat. The particle matter sensor was installed separately below to avoid interference with other sensors. CO2 and CH4 sensors were installed on the separate probe rod so that it could be connected to the main device. The fan is designed to maintain proper airflow. The battery, PWS1S2P-7.0A, with a capacity of 7000 Am, was installed inside of the main device. The battery help measuring a device for 24 h without power. The operation step is to press the on/off button to turn on the device; the device then starts measuring all items and transmits the measured data to the server. When the start/stop button is pressed, the measured information is automatically saved to the server and SD card once per minute. The front MODE button is a touch button, and each time it is touch, the value of the currently measured item can be checked sequentially on the front LED display. The sixteen items to be measured are automatically calibrated, but a manual calibration function is installed in the smartphone application to make it more accurate. The calibration function has a very important effect on the accuracy or precision of the measuring instrument [33]. Manual calibration was made with an arithmetic algorithm to obtain a zero-value using standard gas. The communication unit averages the measured data using Bluetooth and Wi-Fi at 1 min intervals and stores the data in the server and SD card. Figure 5 shows the exterior and interior of the manufactured measuring device.



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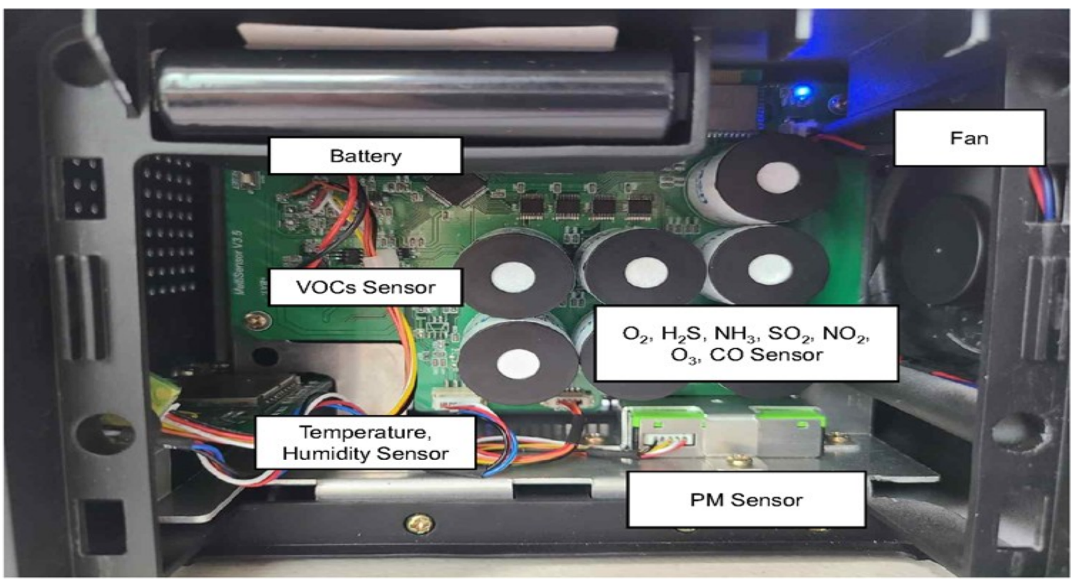


(b)

Structure diagram of the manufactured smartphone application.

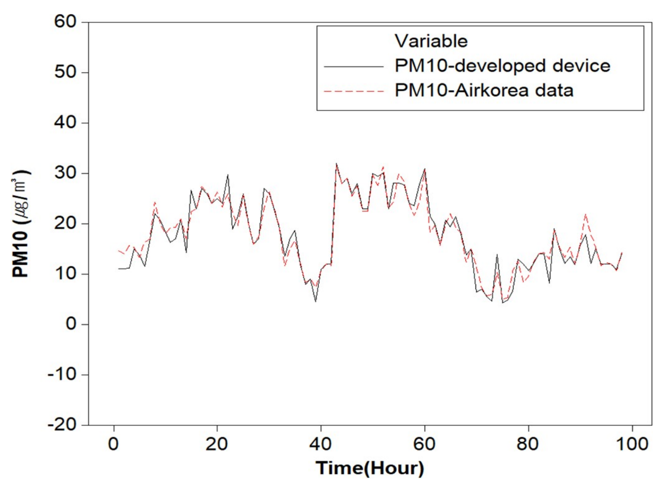
In order to confirm the clear operation of the software, it was tested for 24 h by interworking between the machine and the software, and the alert that was pushed when the measured items were contaminated. In the future, it will be tested over two months for data transmission errors, data transmission speed, and graphing errors.

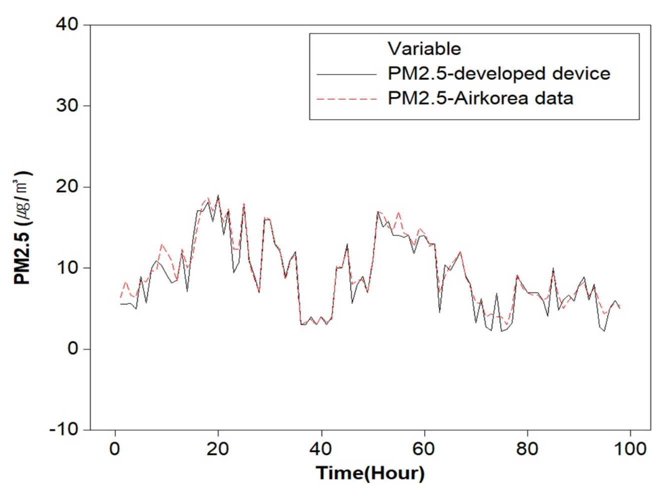
Verification of Multi-Item Air Quality Monitoring System

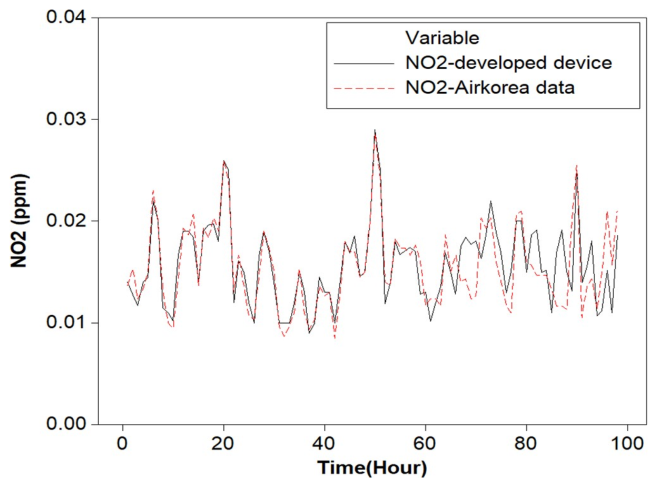
In order to test the reliability of the developed device, a comparative test with other specialized environmental devices, an accuracy test, and an operating temperature test were conducted. Comparative test items were PM10, PM2.5, O3, NO2, CO, and SO2. The accuracy test items were temperature and humidity. The operating temperature test range was 20
C to 60 ◦C. Eight out of the sixteen items were tested; the other items are scheduled to be conducted through a closed chamber test through an accredited testing laboratory.

First, in the comparative test, the values were compared by installing the developed device at the measurement point and the same point of AirKorea (Korea government official atmospheric information site). The environmental measuring instruments used in AirKorea are PM10 for Spirant BAM by Ecotech (Hyderabad, India), PM2.5 for BAM 1020 by Met one Instrument, O3 for Serinus 10 by Ecotech (Hyderabad, India), NO2 for Serinus 40 by Ecotech (Hyderabad, India), CO for Serinus 30 by Ecotech (Hyderabad, India), SO2 for Serinus 50 by Ecotech (Hyderabad, India). They are all environment-specialized measuring devices. They were all tested for a quality device using a professional purpose by the Korea Ministry of Environment. Figure 7 shows the difference between the developed device and AirKorea measuring device for six items (PM10, PM2.5, O3, NO2, CO, SO2). The total test duration was 14 days, and 100 h of data were compared. The difference in values is 5% for PM10, 6% for PM2.5, 4% for O3, 5% for NO2, 7% for CO, and 7% for SO2. PM10 and PM2.5 showed a difference of 5–6%, and it was confirmed that the difference was not much considering that the measurement method was a beta-ray method and a light scattering method. O3, NO2, CO, and SO2 showed a difference of 4–7%. Although there are some differences between these values, it was confirmed that there was no significant difference under the assumption that the measurement and collection methods were different. The result is only a simple comparison test with a specialized measurement device; a clear accuracy test will be confirmed again through a closed chamber test. Through this test,

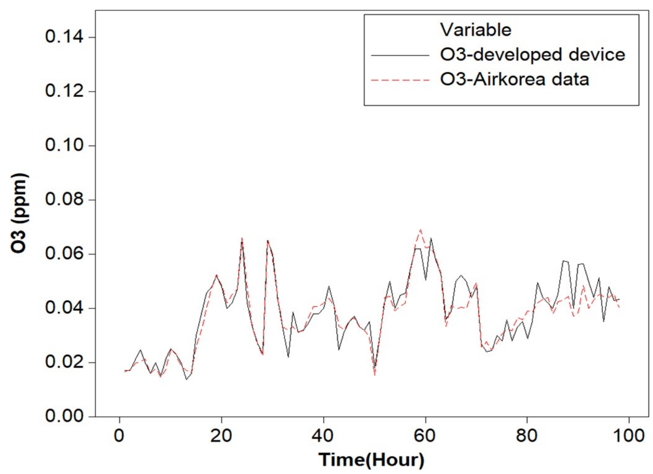
it was confirmed that the measurement trend of the developed device is not significantly different from the existing specialized environmental measurement device.



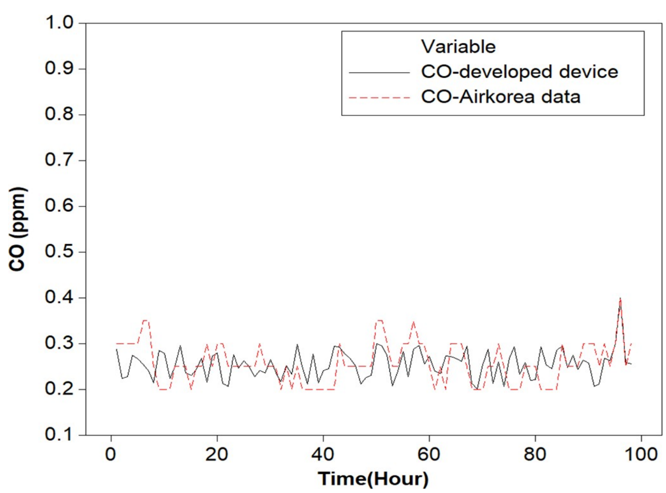




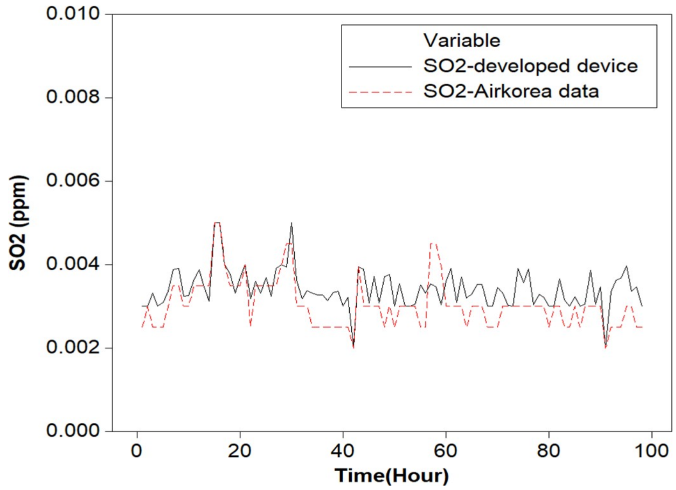
Variable
NO2-developed device
NO2-Airkorea data
NO2 (ppm)
Time(Hour)



Variable
O3-developed device
O3-Airkorea data
O3 (ppm)
Time(Hour)

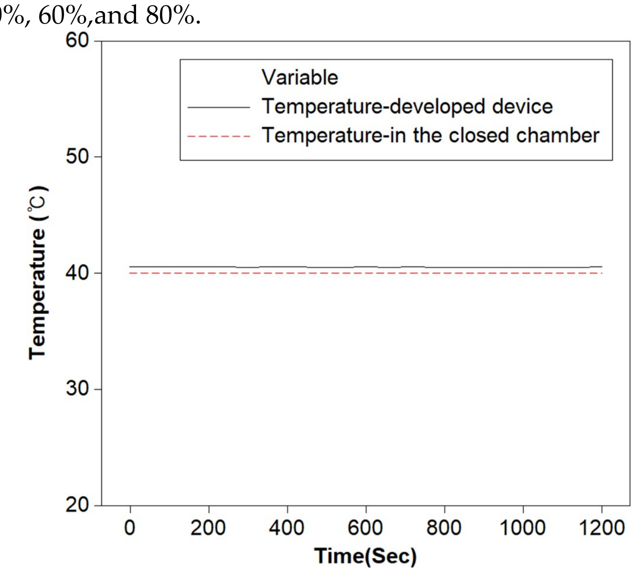


Variable
CO-developed device
CO-Airkorea data
CO (ppm)
Time(Hour)



Comparative test between the developed device and Airkorea data. (a) PM10 results; (b) PM2.5 results; (c) O3 results; (d) NO2 results; (e) CO results; (f) SO2 results.

The temperature and humidity test in Figure 8 was processed in a closed chamber at the nationally accredited testing institution. For the test, a closed chamber was set to a temperature of 40 ◦C and a humidity of 80%. The test was run for 1200 s and showed an accuracy of 99% for temperature and 98% for humidity. Currently, accuracy tests are being conducted at temperatures of 0 ◦C, 20 ◦C, 40 ◦C, and 60 ◦C and humidity of 20%, 40%, 60%,and 80%.



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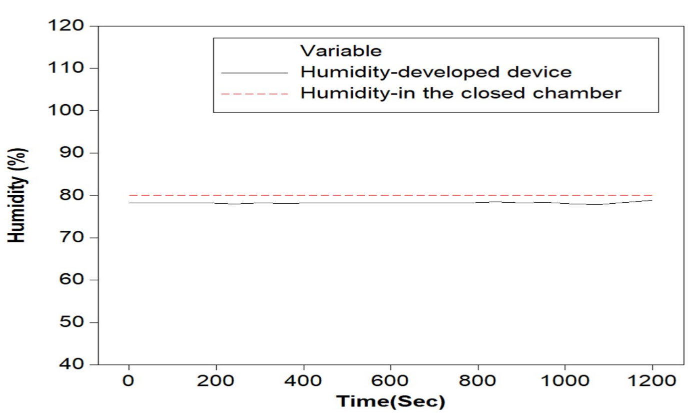
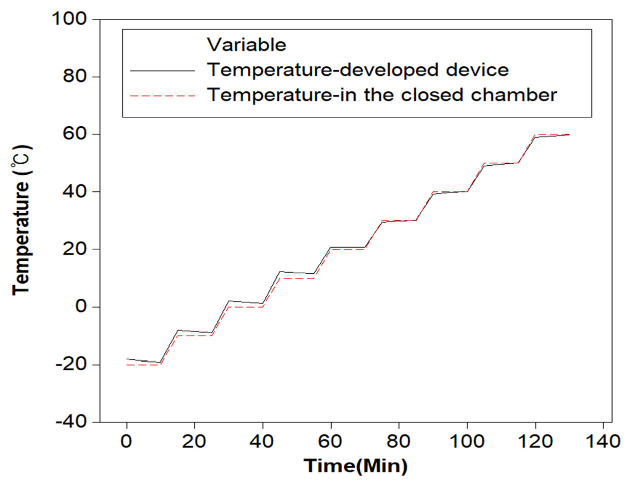


Temperature and humidity accuracy test result by the developed device and the closed chamber environment.
(a) Temperature result; (b) humidity result.
The operating temperature test was confirmed through a closed chamber system of a nationally accredited testing institute. The temperature was divided into nine stages from 20 ◦C to 60 ◦C, and the normal operation of the device was checked. The test time was 130 min, and the result is shown in Figure 9. It was confirmed that the device works well without any problems between −20 ◦C and 60 ◦C.



Therefore, the result shows that the developed system has a positive use for a special- ized air quality measurement device. However, it is not enough to prove the reliability of the developed device considering that the tests conducted are only the comparative test and the simple temperature test. When all installed sensors are tested in a closed chamber and the time and number of tests are sufficient, the device will have a full guarantee fora professional environmental measuring device. Other tests—all sensors in the closed chamber and a comparative test with increased time—are in progress.

Conclusion:

The developed multi-item air quality monitoring system based on real time consists of 16 items (PM10, PM4.0, PM2.5, PM1.0, CO2, CH4, temperature, humidity, VOCs, O2, H2S, NH3, SO2, NO2, O3, and CO). This system was developed by dividing it into hardware (measuring device) and software (smartphone application). To measure sixteen items in the measuring device, ten sensors in the main device and two sensors in the probe rod are installed. All sensors were installed in consideration of the minimum area in the main device. A smartphone application was developed with a home screen, measurement screen, and management screen in consideration of the user's ease of use and clear information delivery. Bluetooth and Wi-Fi are installed for efficient communication between the two devices. Comparative test, temperature–humidity accuracy test, and operating temperature test were conducted to test the availability and reliability of the developed device. It was found to be PM10 5%, PM2.5 6%, O3 4%, NO2 5%, CO 7%, and SO2 7%.
The temperature and humidity accuracy test result showed high reliability at 1% and humidity 2%. The result of the operating temperature test showed that there was no problem in normal operation. However, the test conducted was a comparative test, all installed sensors were not tested, the test time and frequency were not sufficient, and the closed chamber test was not performed. It is not enough to prove the reliability of the developed device. Additional work including a long-term test for more clear

reliability of the device and closed chamber accuracy test for all sixteen item sensors, data acquisition rate, and data transmit rate are necessary for commercializing the device.

This development device will enable real-time environmental monitoring in the near future, and the developed device will be used as a device to help create a better environment for humans.