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Research Article

Air Pollution Monitoring and Control System for Subway Stations Using Environmental Sensors

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The metropolitan city of Seoul uses more energy than any other area in South Korea due to its high population density. It also has high emissions of air pollutants. Since an individual usually spends most of his/her working hours indoors, the ambient air quality refers to indoor air quality. In particular, PM_{10} concentration in the underground areas should be monitored to preserve the health of commuters in the subway system. Seoul Metro and Seoul Metropolitan Rapid Transit Corporation measure several air pollutants regularly. In this study, the accuracy of an instrument for PM measurement using the light scattering method was improved with the help of a linear regression analysis technique to continuously measure the PM_{10} concentrations in subway stations. In addition, an air quality monitoring system based on environmental sensors was implemented to display and record the data of PM_{10}, CO_2, temperature, and humidity. Through experimental studies, we found that ventilation fans could improve air quality and decrease PM_{10} concentrations in the tunnels effectively by increasing the air flow rate.

1. Introduction

People spend most of their time indoors—either at home, in the workplace, or in transit. Thus, there has been an increasing concern over indoor air quality (IAQ) and its effects on public health. The US Environment Protection Agency (EPA) reported that, in the US, the mean daily residential time spent indoors was 21 h, while the GerES II reported that this duration was 20 h in Germany. Thus, the IAQ has been recognized as a significant factor in the determination of the health and welfare of people [1]. The Korea Ministry of Environment (KMOE) enforced the IAQ act to control five major pollutants, including PM_{10}, CO_2, CO, VOCs, and formaldehyde in indoor environments. Out of these, the IAQ standard for PM_{10} concentration is 150 μg/m^3. The IAQ is critical not only in buildings but also in underground areas and public transportation systems. Much effort has been made for the improvement of the IAQ in subway stations [2–5].

Among the various types of indoor environments, underground subway stations have especially unique features. The confined space occupied by the underground subway system can accumulate the pollutants entering from the outside in addition to those generated within the system. Therefore, it is likely that the subway system in the Seoul metropolitan area contains different types of hazardous pollutants due to the old ventilation and accessory systems [3, 6].

Recently, Platform Screen Doors (PSDs) were installed and are being used in many subway stations in Korea to prevent the diffusion of air pollutants into the subway stations and ensure the safety of the public. Some previous studies reported that the PM concentration in subway stations significantly reduced after the installation of PSDs [7, 8]. However, they suggested that the PM concentration in the tunnels would be much higher due to the interruption of particle diffusion into the subway stations by the PSDs. Moreover, most of the ventilation fans may not be working properly because of their deterioration and the high operational cost. Therefore, the PM concentrations in the tunnels have probably been high for a long period of time.

The IAQ in the subway stations can be affected by many factors, such as the number of passengers, the outside conditions, and the natural ventilation rate [9, 10]. The management and monitoring of IAQ in subway stations have become an important issue of public interest [11–13]. Some environmental sensors are important for monitoring IAQ in subway systems and they provide the data needed for continuous online implementation. Sometimes, these sensors in subway stations suffer from poor quality of data and the unreliability of the sensor due to the highly deteriorated and polluted environment, which may cause the measuring instruments installed for monitoring to malfunction. The quality of the online measurement can determine the failure or success of IAQ monitoring and assessment. Although most researchers and practitioners agree with this opinion, very little attention has been given to the study of sensors in a realistic manner [14, 15].

In this study, the accuracy of the instrument for PM measurement using light scattering method was improved with the help of a linear regression analysis technique to continuously measure the PM_{10} concentrations in the subway stations [16]. In addition, the air quality monitoring system based on environmental sensors was implemented to display and record the data on PM_{10}, CO_2, temperature, and humidity [17, 18]. Finally, for underground subway stations with natural ventilation, some ventilation fans were installed in order to improve the air quality in the tunnels. Through experimental studies, we found that the ventilation fans could improve the air quality in the tunnels and decrease the PM_{10} concentration in the tunnels effectively by increasing their air flow rate.

2. Experimental Methods

2.1. PM Measuring Instruments. Particulate matter with an aerodynamic diameter less than 10 μm (PM_{10}) is one of the major pollutants in subway environments. The PM_{10} concentration in the underground areas should be monitored to protect the health of the commuters in the underground subway system. Seoul Metro and Seoul Metropolitan Rapid Transit Corporation measure several air pollutants regularly. As for the PM_{10} concentration, generally, measuring instruments based on β-ray absorption method are used. In order to keep the PM_{10} concentration below a healthy limit, the air quality in the underground platform and tunnels should be monitored and controlled continuously. The PM_{10} instruments using light scattering method can measure the PM_{10} concentration once every several seconds. However, the accuracy of the instruments using light scattering method has still not been proven since they measure the particle number concentration rather than the mass concentration [19].

Table 1: Specifications of PM measuring instruments.

Instrument	Ebam	Esampler	HCT-PM326
Method	β-ray absorption	Light scattering	Light scattering
Range	0~100 mg/m^3	0~65 mg/m^3	0~1 mg/m^3
Sampling flow rate	16.7 L/min	2 L/min	0.8 L/min
Sampling period	60 min	1 sec	6 sec

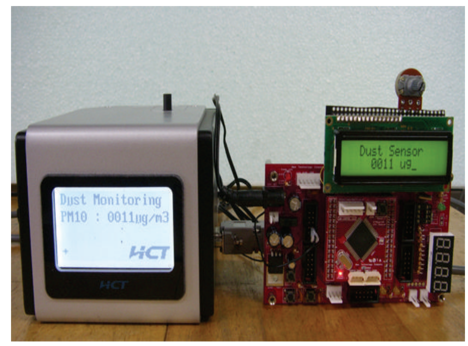


Figure 1: The PM measuring instrument HCT-PM326 connected to ATmega128(L) CPU board.

The purpose of this work is to study the accuracy improvement of the instruments which use light scattering method to continuously measure the PM_{10} concentrations in the underground subway stations. One instrument using β-ray absorption method Ebam (Met one instrument, USA) and two different instruments using light scattering method, that is, Esampler (Met one instrument, USA) and HCT-PM326 (HCT, Korea), were installed on the platform at "Jegi" subway station of Seoul Metro line number 1 in order to evaluate their dynamic performances. The specifications of the PM measuring instruments are listed in Table 1. Figure 1 shows the PM measuring instrument HCT-PM326 connected to the ATmega128(L) CPU board, which is used to display the measured data and transfer them to an m2m wireless modem.

2.2. CO_2 Sensor. Of late, the monitoring of carbon dioxide (CO_2) has been considered very important for passengers and employees in underground subway stations due to the health risks associated with carbon dioxide exposure. For instance, headache, sweating, dim vision, tremors, and loss of consciousness are caused by exposure to high CO_2 concentration for a long time.

CO_2 gas sensors being used presently can be divided into two types. The first one is NDIR (Nondispersive Infrared) method and the second one is a chemical method. They are commonly available for monitoring CO_2 concentrations indoors. However, chemical CO_2 sensors have many limitations that prevent their application to a variety of practical fields. The obvious drawbacks of chemical CO_2 sensors are short-term stability and low durability. This is because chemical sensors are easily deteriorated by heterogeneous gases and minute particles in the ambient polluted air. On the

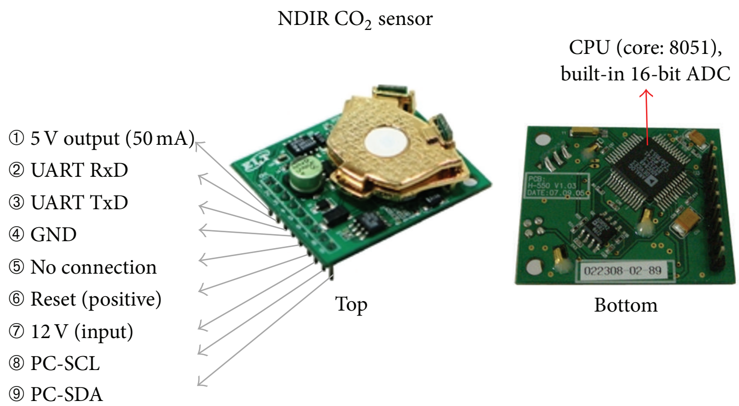


Figure 2: Pin assignment of the NDIR CO_2 sensor H-550 (ELT, Korea).

Table 2: Specifications of the NDIR CO_2 sensor H-550.

Range	0~50,000 ppm
Sensitivity	±20 ppm ± 1%
Accuracy	±30 ppm ± 5%
Response time (90%)	Within 30 sec

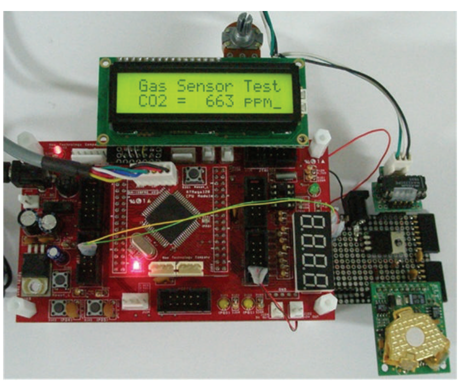


Figure 3: The NDIR CO_2 sensor H-550 connected to ATmega128(L) CPU board.

other hand, since the NDIR method uses the physical sensing principle, such as gas absorption at a particular wavelength [20], NDIR sensors are more advanced in terms of long-term stability and accuracy during CO_2 measurement. Hence, NDIR CO_2 sensors are the most widely applied for real-time monitoring of CO_2 concentration [21]. The pin assignment of the NDIR CO_2 sensor H-550 manufactured by ELT Co. Ltd., Korea, and its connection to ATmega128(L) CPU board are shown in Figures 2 and 3, respectively. The specifications of the NDIR CO_2 sensor H-550 are listed in Table 2.

2.3. Temperature and Humidity Sensor. Seoul Metropolitan Rapid Transit Corporation measures temperature and humidity as well as PM_{10} and CO_2 in the waiting rooms of the subway stations regularly. Temperature and humidity can also be used for the analysis and prediction of IAQ in a subway station [22–24]. As for temperature and humidity sensors, the

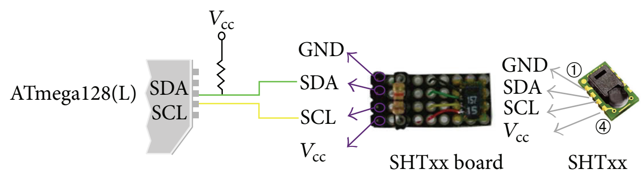


Figure 4: Pin assignment of the temperature and humidity sensor SHT11.

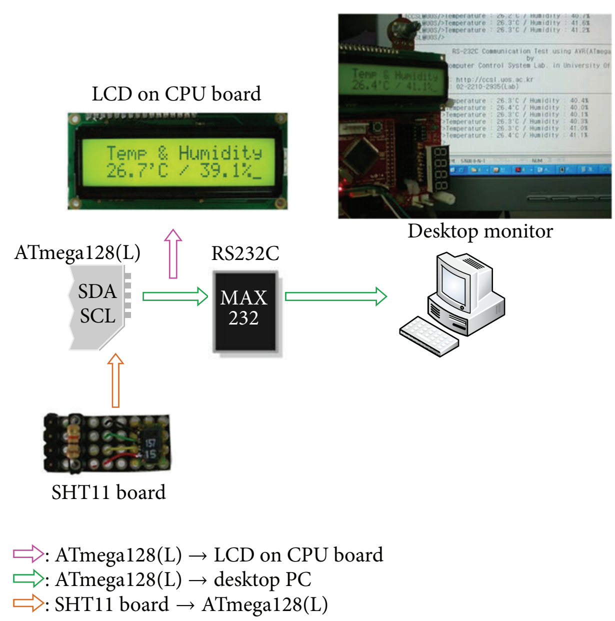


Figure 5: The temperature and humidity sensor SHT11 connected to the ATmega128(L) CPU board.

SHT11 manufactured by Sensirion was chosen in this study. It is a single chip relative humidity and temperature multisensor module, comprising a calibrated digital output. It is coupled to a 14-bit analog to digital converter and the 2-wire serial interface and internal voltage regulation, which allow easy and fast system integration. The pin assignment of SHT11 is shown in Figure 4. Figure 5 shows that the SHT11 is connected to ATmega128(L) CPU board, which transmits temperature

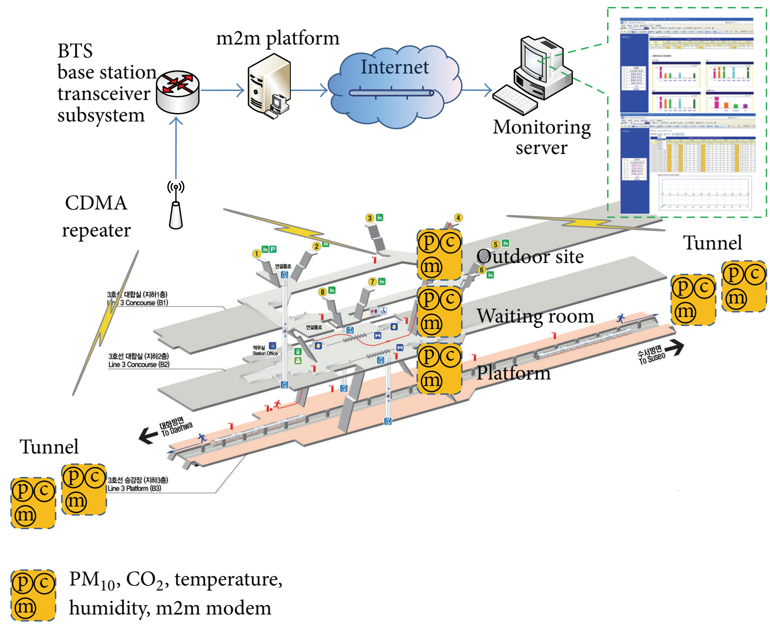


Figure 6: Air quality monitoring system for subway stations.

Table 3: Specifications of the temperature and humidity sensor SHT11.

Temperature range/accuracy	−40~123.8°C/±0.4°C
Humidity range/accuracy	0~100%/±3.0%

and humidity data to the desktop PC using RS232C interface. The measuring range and accuracy of SHT11 are given in Table 3.

2.4. Air Quality Monitoring System in a Subway Station. This paper presents the implementation of an IAQ monitoring system, which uses sensor modules for measuring PM_{10}, CO_2, temperature, humidity, and a data processing module with CDMA (Code Division Multiple Access) communication capabilities for the transmission and management of the measurement results. The need for air quality measuring over large underground subway areas, such as waiting rooms, platforms, and tunnels, necessitates wireless connectivity for the measuring device. Wireless sensor networks represent a vast and active research area in which a large number of applications have been proposed, including indoor air quality monitoring and control [25], structural health monitoring [26], and traffic monitoring [27]. Figure 6 shows an air quality monitoring system for subway stations. The sensor and CDMA modules were installed at a waiting room, a platform, an outdoor site, and tunnels. MDT-800 (Telit, UK) is used for CDMA communication modules, while the MDT-800 is a complete modem solution for wireless m2m applications. The MDT-800 with a frequency band of about 800 MHz is ideally suited for real-time monitoring and control applications without the need for human intervention between remote machines and back office services. The measured air quality data were transmitted to the m2m platform via the CDMA

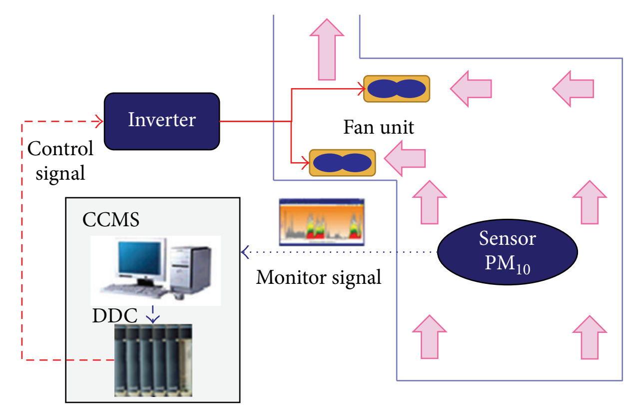


Figure 7: Ventilation fans and control systems installed at the natural ventilation point in the tunnel.

Repeater and the BTS (Base station Transceiver Subsystem), eventually reaching the air quality monitoring server through the internet.

2.5. Ventilation Fan System to Control IAQ in a Subway Station. The PSDs improved the indoor air quality in subway stations. However, the air quality in the subway tunnels became worse. Therefore, ventilation systems are needed to improve the air quality in the subway tunnels. Some subway stations of Seoul Metro line number 1 had no ventilation systems for tunnels, "Jegi" subway station being one of them. In this study, we tried to improve the air quality by installing ventilation fans at the natural ventilation points in the tunnel at "Jegi" subway station. Figure 7 shows the ventilation fans and control systems installed at the natural ventilation points of the tunnel. The Central Control and Monitoring System (CCMS) monitored the PM_{10} concentration in the tunnel. It

TABLE 4: Specifications of the ventilation fan.

Input voltage	220 V
Rated power	600 W
Rated speed	1,750 rpm
Static pressure	15~20 mmAq
Air volume	3,600 CMH

FIGURE 8: Ventilation fans installed at the natural ventilation point in the tunnel at "Jegi" subway station.

controls the inverter of the ventilation fans so that if the air quality in the tunnel deteriorates and the PM_{10} concentration increases more than the permissible limit, it can operate the ventilation fans using the Direct Digital Control (DDC). Figure 8 shows the ventilation fans installed at the natural ventilation point in the tunnel at "Jegi" subway station. The specifications of the ventilation fan are listed in Table 4.

3. Results and Discussion

3.1. Accuracy Improvement of the PM Measuring Instruments HCT and Esampler. A linear regression analysis method was used to improve the accuracy of HCT using the light scattering method. The data measured by this PM measuring instrument had to be converted to actual PM_{10} concentrations using some factors. One instrument using β-ray absorption method (Ebam) and the other instruments using light scattering method (HCT, Esampler) were installed and measurements were taken on the platform of a subway station of Seoul Metro line number 1 for 5 days as shown in Figure 9. The measured PM_{10} concentrations of Ebam and HCT are shown in Figure 10. The RMSE (Root Mean Square Error) in Figure 10 was 72.5227 $\mu g/m^3$. Using the linear regression analysis technique shown in Figure 11, the measured PM_{10} concentration of HCT in Figure 10 can be corrected as shown in Figure 12. The RMSE in Figure 12 was 17.7128 $\mu g/m^3$. In Figure 11, the correlation coefficient R^2 was 0.9324. Next, the measured PM_{10} concentrations of Ebam and Esampler are shown in Figure 13. The RMSE in Figure 13 was 94.7440 $\mu g/m^3$. Using the linear regression analysis technique shown in Figure 14, the measured PM_{10} concentration of Esampler in Figure 13 can be corrected as shown in Figure 15. The RMSE in Figure 15 was 22.6132 $\mu g/m^3$. In Figure 14, the correlation coefficient R^2 was 0.8818. It can be seen in Figures

FIGURE 9: PM measuring instruments installed in "Jegi" subway station.

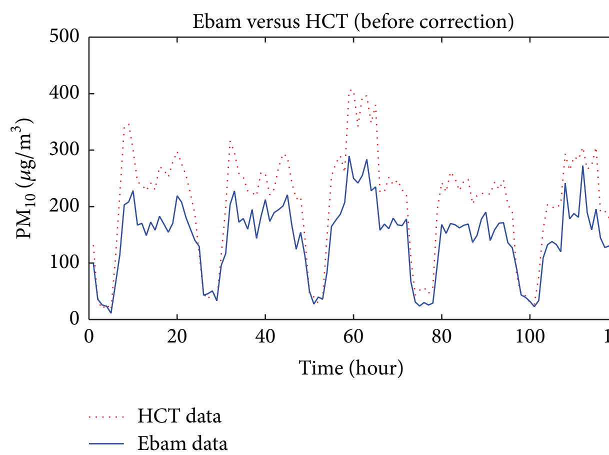


FIGURE 10: PM_{10} concentrations of Ebam and HCT measured on the platform of "Jegi" subway station.

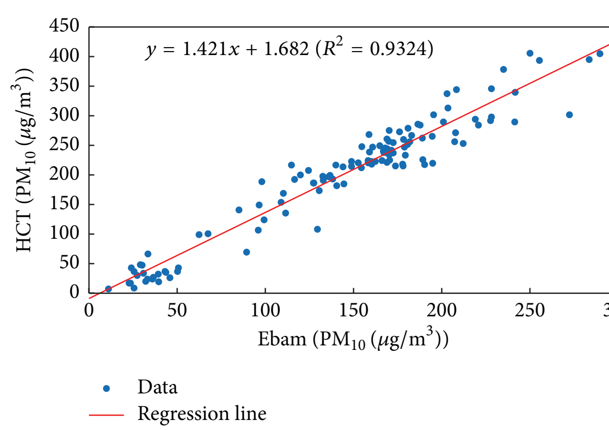


FIGURE 11: Linear regression analysis.

12 and 15 that the measured PM_{10} concentrations of HCT and Esampler are very similar to that of Ebam if they are corrected using a linear regression analysis technique. This finding suggests that the PM measuring instruments using light scattering method can be used to measure and control the PM_{10} concentrations of the underground subway stations. Because HCT is much cheaper than Esampler and is better in RMSE, we chose HCT to measure the PM_{10} concentrations

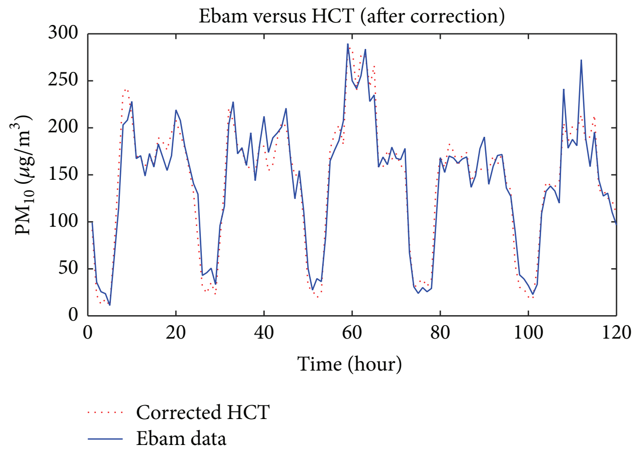


FIGURE 12: PM_{10} concentrations corrected using a linear regression analysis.

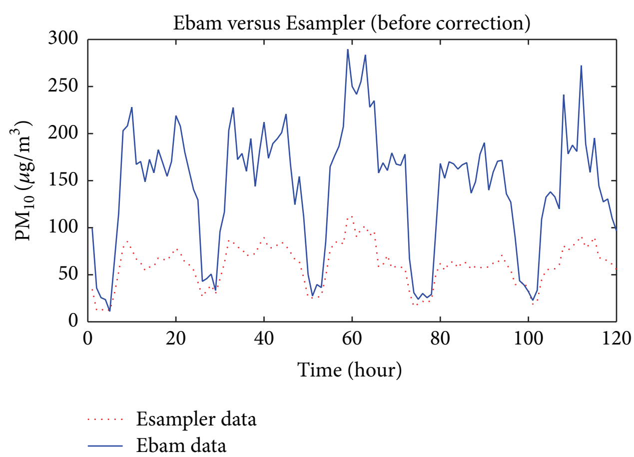


FIGURE 13: PM_{10} concentrations of Ebam and Esampler measured on the platform of "Jegi" subway station.

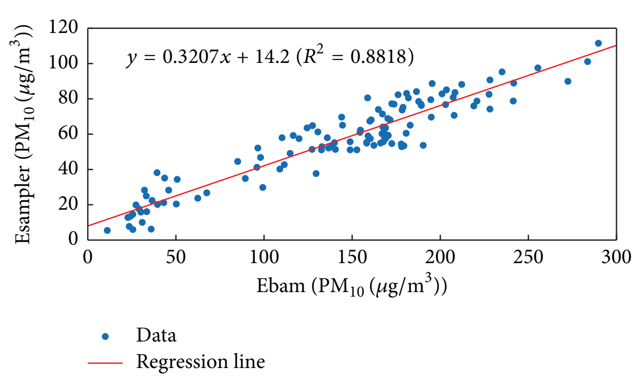


FIGURE 14: Linear regression analysis.

of the underground subway stations. However, because of Fe-containing particles, the particles in tunnel are heavier than those of same size in waiting room, platform, and outdoor site. So, the calibration of Figure 12 should be done for every location such as tunnel, waiting room, platform, and outdoor site.

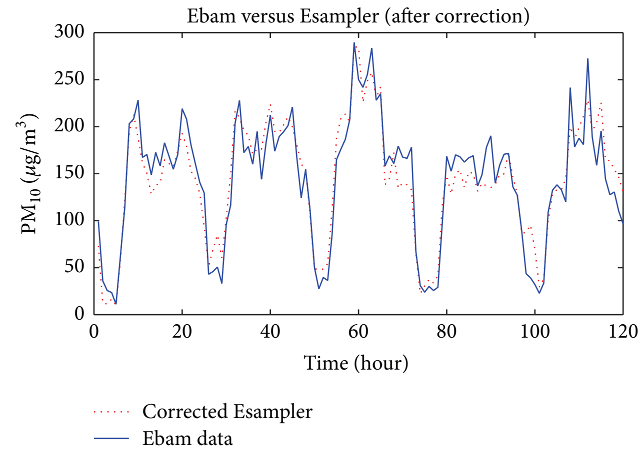


FIGURE 15: PM_{10} concentrations corrected using a linear regression analysis.

3.2. Monitoring of Air Quality in a Subway Station. The air quality measuring instruments for PM_{10}, CO_2, temperature, and humidity were installed in the waiting room, platform, and tunnel and at the outdoor site of "Daecheong" subway station of Seoul Metro line number 3 as shown in Figure 16.

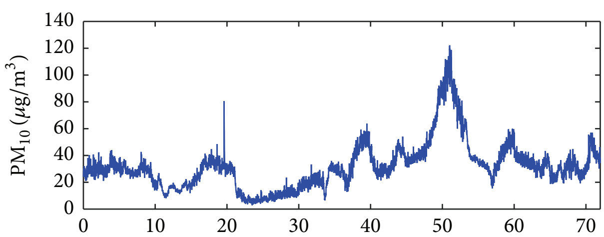
The PM_{10}, CO_2, temperature, and humidity data which were measured in the waiting room of "Daecheong" subway station for 3 days at a sampling interval of 30 sec are shown in Figure 17. As for the PM_{10} concentration, it was kept under 120 μg/m^3, which met the KMOE's IAQ standard for PM_{10} concentration (150 μg/m^3). As for CO_2 concentration, it was kept between 400 and 580 ppm, which met the KMOE's IAQ standard for CO_2 concentration (1000 ppm). The temperature of the waiting room was 29–32°C and the relative humidity was 53–73%. Figure 18 shows the results for the platform at "Daecheong" subway station. The PM_{10} concentration was kept under 75 μg/m^3, which was lower than that in the waiting room. This was due to the PSDs, which blocked the dust from the tunnel. In addition, the ventilation fans on the platform were operated more frequently compared to those in the waiting room because passengers gather at the platform. The CO_2 concentration was 500–700 ppm, which was a little higher than that in the waiting room. It was because of the crowd of passengers. Temperature of the platform was 31–33°C and the relative humidity was 50–64%.

Figure 19 shows the results for the tunnel between "Daecheong" and "Hangnyeoul" subway stations. The PM_{10} concentration was 40–400 μg/m^3, which was much higher than KMOE's IAQ standard for PM_{10} concentration (150 μg/m^3). However, it was lower than 50 μg/m^3 when the train stopped for 4 hours (1:00 a.m.–5:00 a.m.). Most of the ventilation fans may not have been in working condition because of their deterioration and high running cost. Therefore, the PM_{10} concentration in tunnels might have been high for a long period of time. The CO_2 concentration in the tunnel was 400–800 ppm, while the temperature was 27–31°C and the relative humidity was 60–80%.

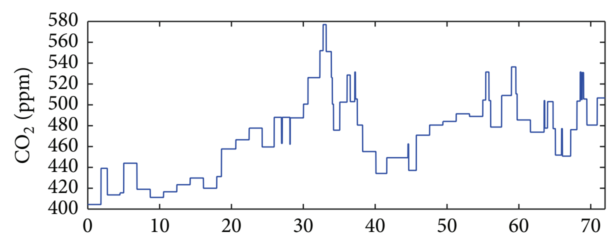
Finally, the data for the outdoor site at "Daecheong" subway station are shown in Figure 20. The PM_{10} concentration

(a) Waiting room (b) Platform (c) Tunnel (d) Outdoor site

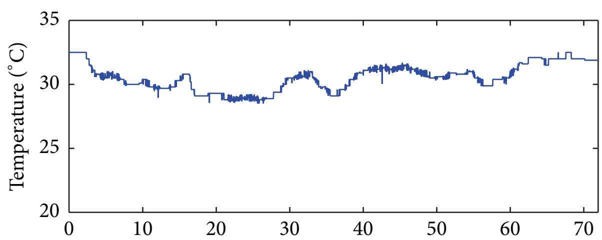
Figure 16: Air quality measuring instruments installed at "Daecheong" subway station.



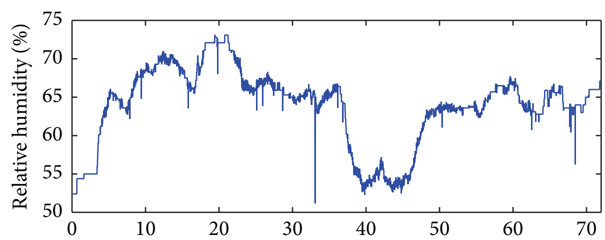
(a) PM_{10} concentration



(b) CO_2 concentration



(c) Temperature

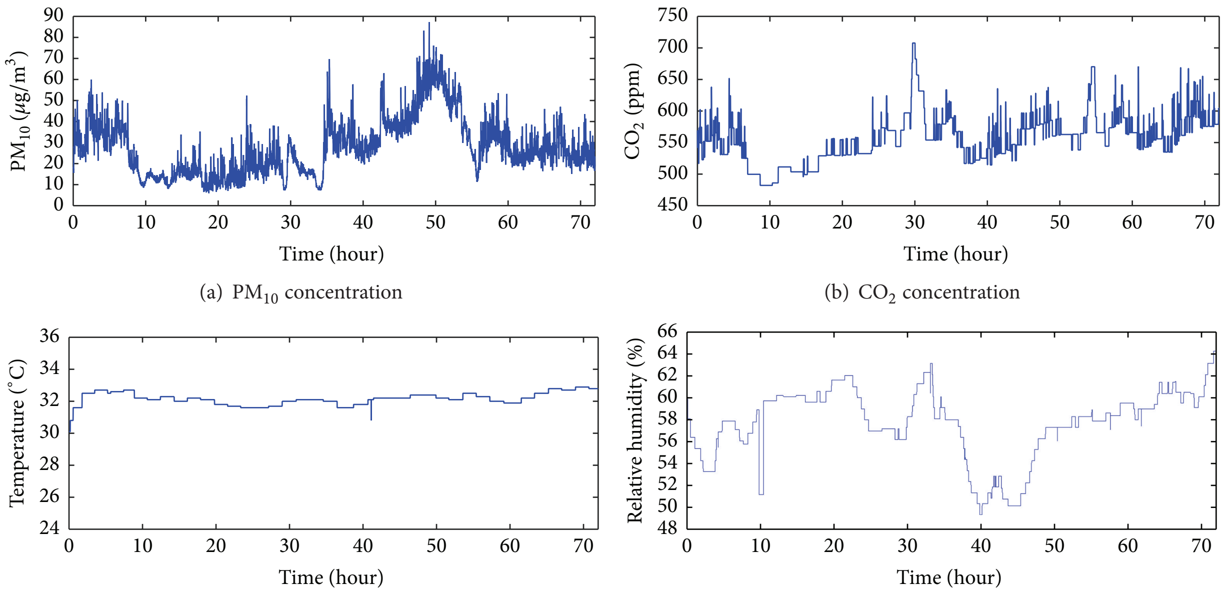


(d) Relative humidity

Figure 17: PM_{10}, CO_2, temperature, and relative humidity in the waiting room of "Daecheong" subway station.

was approximately 10–100 $\mu g/m^3$ except for two cases in which it was higher than 700 $\mu g/m^3$. The air quality of the outdoor site at "Daecheong" subway station was relatively good. The cause of the generation of two-pulse data is that the PM_{10} concentration was measured using light scattering method. One of the demerits of light scattering method is that, sometimes, it gives very large values. Environmental sensors are important components for monitoring the IAQ in subway systems, as they provide the data needed for continuous online implementation. Sometimes, these sensors suffer from poor data quality and sensor reliability due to the hostile environment in the subway stations in which the measuring instruments are installed for monitoring. They may even fail for a long period of time as indicated in Figure 20(a). These failures could reduce the accuracy and reliability of the measurement, which may result in an erroneous control action and false perception regarding the performance of the monitoring system. Faulty sensors that have either completely or partially failed could provide incorrect information regarding monitoring and control. Therefore, many researchers have tried to prevent these problems [23, 28–30]. The CO_2 concentration of the outdoor site was 400–520 ppm, while the temperature was 24–35°C and the relative humidity was 50–90%. It can be seen that the relative humidity is inversely proportional to temperature.

3.3. IAQ in the Tunnel Controlled Using Ventilation Fan System. As mentioned earlier, the tunnel at "Jegi" subway station has no ventilation systems. Therefore, we installed ventilation fans at the natural ventilation points of the tunnel to improve the air quality, as shown in Figure 8. The CCMS monitors the PM_{10} concentration in the tunnel and controls the inverter of the ventilation fans using the DDC. Figure 21 shows the experimental results of the PM_{10} concentration of the tunnel at "Jegi" subway station with offline fan control for 25 days. At first, the ventilation fans were stopped for 5 days to investigate the effects of the ventilation fans. Subsequently, the speed of the fans was set to 60 Hz for 8 days and then to 70 Hz for 6 days. Finally, for 5 days, it was set to 75 Hz during rush hours and 60 Hz during off-peak hours to decrease the



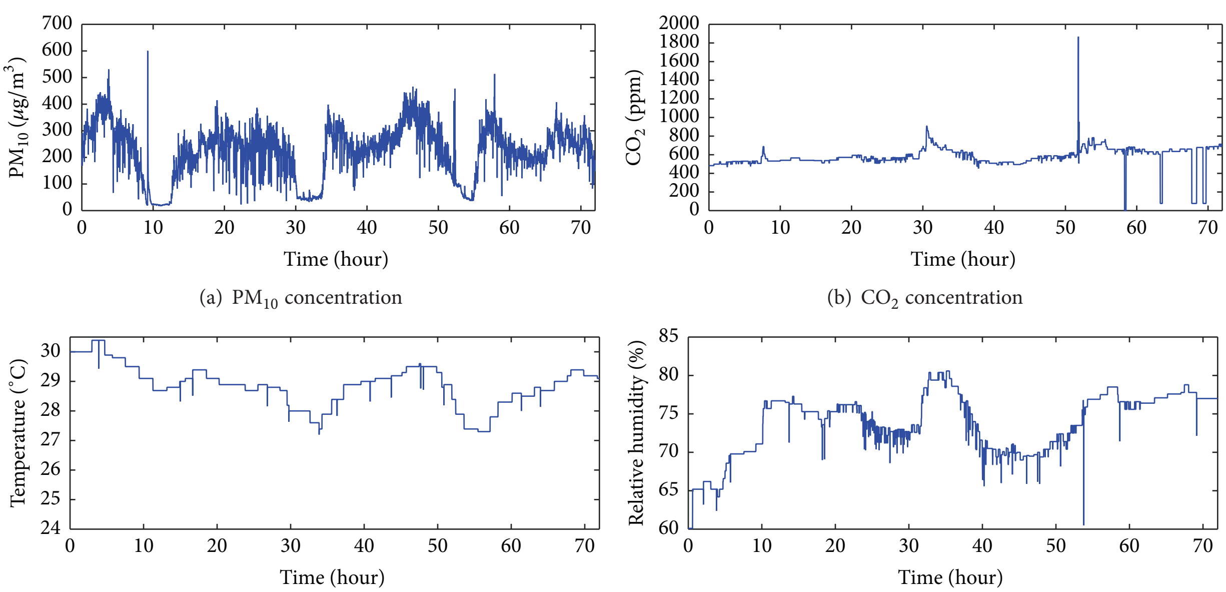
(a) PM$_{10}$ concentration

(b) CO_2 concentration

(c) Temperature

(d) Relative humidity

FIGURE 18: PM$_{10}$, CO_2, temperature, and relative humidity at the platform of "Daecheong" subway station.



(a) PM$_{10}$ concentration

(b) CO_2 concentration

(c) Temperature

(d) Relative humidity

FIGURE 19: PM$_{10}$, CO_2, temperature, and relative humidity inside the tunnel between "Daecheong" and "Hangnyeoul" subway stations.

loss of electric energy. Through experimental studies, we found that the PM$_{10}$ concentration of the tunnel could be decreased by increasing the air flow rate of the ventilation fans (by increasing the speed of the ventilation fans). We also noted an abrupt increase in the PM$_{10}$ concentration when the fans were stopped for a day before the experiments were completed.

Figure 22 shows the experimental results of the PM$_{10}$ concentration in the tunnel at "Jegi" subway station with online fan control for 85 days. Initially, the ventilation fans were stopped for 2 weeks. Then, as shown in Figure 7, the DDC controlled the speed of the fans at 60, 70, or 75 Hz depending on the PM$_{10}$ concentration in the tunnel for 10 weeks. As shown in Figure 22, we found that the air quality in the tunnel could be improved gradually by using the ventilation fans, although it might cause the IAQ to be affected by the ambient air.

4. Conclusions

An air quality monitoring system based on environmental sensors was implemented to display and record the data of

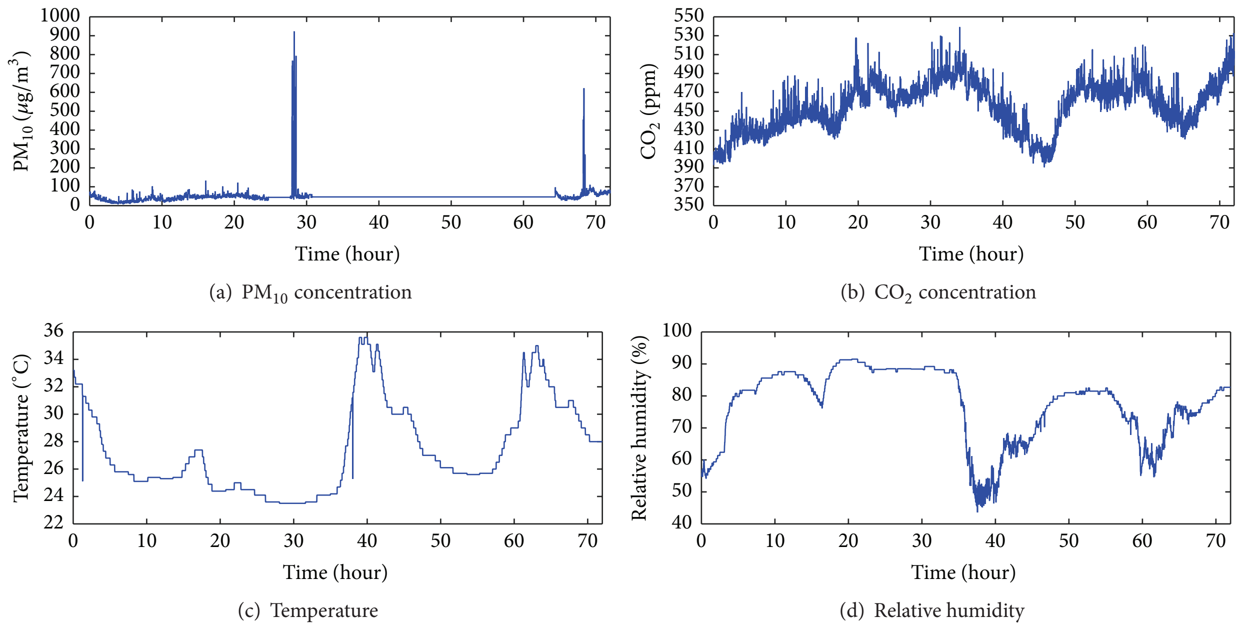


FIGURE 20: PM_{10}, CO_2, temperature, and relative humidity at the outdoor site of "Daecheong" subway station.

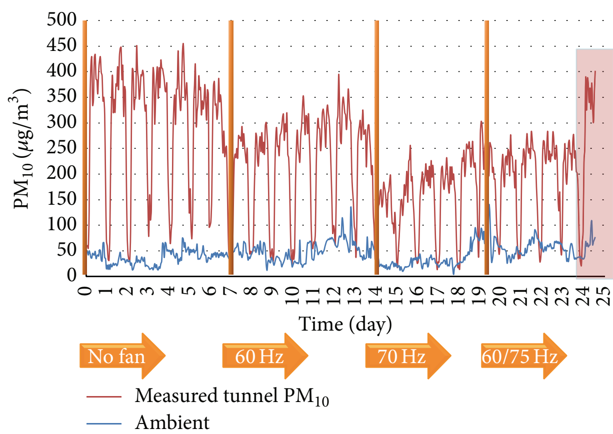


FIGURE 21: PM_{10} concentration in the tunnel and the ambient air of "Jegi" subway station with offline fan control.

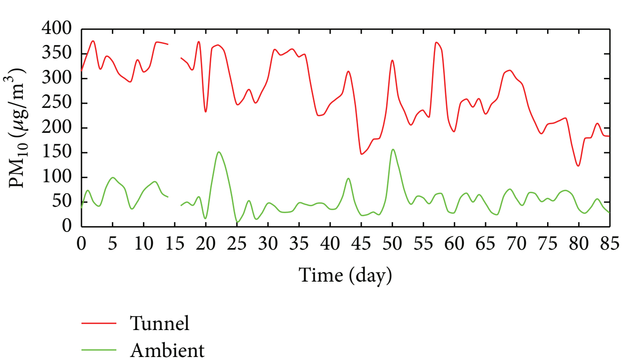


FIGURE 22: PM_{10} concentration in the tunnel and the ambient air of "Jegi" subway station with online fan control.

PM_{10}, CO_2, temperature, and humidity of waiting rooms, platforms, tunnels, and outdoor sites at underground subway stations. The accuracy of the PM measuring instruments using light scattering methods was improved with the help of a linear regression analysis technique to continuously measure the PM_{10} concentrations in the subway stations. Even though the accuracy was greatly improved, this approach had its demerits, such as the generation of very large measured data and the need to repeat the linear regression analysis every time the PM measuring instruments were moved to other places.

Ventilation fans were installed at the natural ventilation points in the tunnel to improve its air quality. Through some experimental studies, we found that the PM_{10} concentration of the tunnel could be decreased by increasing the rate of air flow from the ventilation fans. Thus, the air quality of the tunnel could be improved by using the ventilation fans, although it might cause the IAQ to be affected by the ambient air. Therefore, some strategies for controlling the ventilation fan should be implemented such that the ventilation system should switch off when the air quality outside is very poor.

Competing Interests

The authors declare that they have no competing interests.

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