Journal of Cleaner Production 133 (2016) 212–219

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

A novel control system for nitrogen dioxide removal and energy saving from an underground subway stations

Youn-Suk Son [a], Jin-Ho Jeong [b], Hyung Joo Lee [c], Jo-Chun Kim [b], *

[a] Research Division for Industry & Environment, Korea Atomic Energy Research Institute, Jeongeup-si, Jeollabuk-do 580-185, Republic of Korea
[b] Department of Environmental Engineering, Konkuk University, Seoul 143-701, Republic of Korea
[c] NASA Postdoctoral Program, NASA Ames Research Center, Moffett Field, CA 94035, USA

ARTICLE INFO

Article history:
Received 23 March 2016
Received in revised form
20 May 2016
Accepted 22 May 2016
Available online 27 May 2016

Keywords:
Nitrogen dioxide (NO_2)
Activated carbon
Adsorption
Indoor air quality (IAQ)
Subway
Energy saving

ABSTRACT

The importance of indoor air quality in a subway system is growing rapidly because passengers' health and displeasure are interrelated. Among diverse indoor pollutants, nitrogen dioxide (NO_2) emitted from automobiles may flow into a platform of underground subway through ventilation holes or stairs. The level of NO_2 in an underground subway station should be managed to prevent its adverse effects because NO_2 is harmful to health. In this study, a novel control system (self-control system) equipped with panel-type hybrid activated carbon beds were developed and applied to remove NO_2 and save energy for ventilation from underground subway stations. To evaluate the removal efficiency by varying influential factors such as superficial gas velocity and relative humidity, we measured the NO_2 concentration from diverse sampling points (ambient, platform, and before and after the hybrid activated carbon bed) before and after operating the self-control system. As a result, the NO_2 concentration at the ventilation hole of the subway station (12.3–113.6 ppb) was higher than that at the air monitoring station (9.2–68.4 ppb, AIRKOREA operated by Ministry of Environment in Korea). The level of NO_2 was changed by varying the relative humidity in ambient air. The removal efficiency of NO_2 decreased from 66.3% to 60.5% and the pressure drop of hybrid activated carbon bed in the system increased from 2.2 mmAq to 5.4 mmAq when the superficial gas velocity (depending on inverter frequency) increased from 1.04 m/s to 1.82 m/s. Additionally, the removal efficiency of NO_2 rapidly decreased with elapsed time and was affected by relative humidity and weather conditions. Finally, the level of NO_2 in the platform was less than 50 ppb (which is the standard value recommended by the Ministry of Environment, Korea), when the hybrid activated carbon bed was set to 90° (vertical direction on air flow). When the self-control system was operated in the heating ventilating, and air conditioning system of the underground subway station, the NO_2 level in the platform was considerably controlled to below 50 ppb and the power consumption for ventilation reduced.

1. Introduction

Subway systems in metropolitan area around the world do not only represent public transport system for citizens, but also it is more economical and eco-friendly than automobiles (Lu, 2016, 2015; Song et al., 2014). Accordingly, the importance of indoor air quality (IAQ) in the subway system is growing rapidly (Kim et al., 2012; Ma et al., 2015; Sohn et al., 2008; Son et al., 2014a, 2014b, 2013). In particular, IAQ at a platform is more important than that at a waiting room because a passenger spends more time in a platform compared with a waiting room. Thus, improving the air quality at a platform should be given priority because passengers' health and displeasure are interrelated (Li and You, 2011; Park and Ha, 2008).

It is reported that the IAQ in underground subway stations is affected by outdoor air (Lee et al., 2002; McAdam et al., 2011; Park et al., 2012). Specially, nitrogen dioxide (NO_2) is a representative pollutant generated by urbanization and industrialization (Pleijel et al., 2009). NO_2 emitted from automobiles may flow into a platform of underground subway through ventilation holes or stairs (Kim et al., 2008; Kraft et al., 2005; Skene et al., 2010). Therefore, the level of NO_2 in a platform can vary in proportion to traffic volume and citizens' activity (Kim et al., 2008; Lee et al., 2002; Skene et al., 2010).

---

* Corresponding author. Tel.: +82 2 450 4009; fax: +82 2 455 2994.
E-mail address: jckim@konkuk.ac.kr (J.-C. Kim).

http://dx.doi.org/10.1016/j.jclepro.2016.05.116

Therefore, the level of NO_2 in the platform should be managed to prevent its adverse effects because NO_2 is harmful to health (Kattan et al., 2007; Kraft et al., 2005; Yoo et al., 2015). Long-term exposure to NO_2 causes increased susceptibility to lower respiratory tract illness (Folinsbee, 1992; Melia et al., 1977; Neas et al., 1991). Moreover, NO_2 is also associated with increased risk of chronic obstructive pulmonary disease mortality (Meng et al., 2013). In acute and chronic animal exposure tests, mice exposed to NO_2 experienced greater mortality from induced bacterial or viral infections compared to mice not exposed to NO_2 (Ehrlich and Henry, 1968; Ehrlich et al., 1977; Folinsbee, 1992; Gardner et al., 1977). In addition, it has been reported that NO_2 exposure is a potential inducer of neurological diseases (Li et al., 2012).

Heating, ventilating, and air conditioning (HVAC) systems are installed in most of underground subway stations to provide comfortable and fresh air to underground subway stations; however, some these facilities are outdated and need reorganization. A lot of HVAC systems are equipped with air filters to supply fresh air to platforms (Kwon et al., 2011; Montgomery et al., 2012). However, it is very difficult to remove gaseous pollutants such as NO_2 by these filters. For the removal of NO_2, many technologies such as plasma, catalytic oxidation, and photocatalyst have been developed (Caneghem et al., 2016; Chen and Chu, 2011; Dvořák et al., 2010; Moscosa-Santillan et al., 2008; Stasiulaitiene et al., 2016). However, these conventional control technologies are more appropriate to industrial facilities than HVAC systems of underground subway stations because conventional methods have some problems such as formation of by-products and high-energy consumption (Tran et al., 2004; Wu and Radovic, 2005).

On the other hand, energy efficiency is significant to improve environmental and social sustainability, and economic performance. Improved energy efficiency also relieves climate change by reducing emissions of greenhouse gases (Lee et al., 2014). From an energy consumption standpoint, underground subway systems are also huge energy consumers at regional level. It is reported that one third of the network's energy is required for operating the subsystems of subway stations and surroundings such as ventilation (Giretti et al., 2012). In case of Beijing subway, the energy consumption of a subway station is 9500 kWh every day, and the proportion of the HVAC system energy consumption is approximately 64% (Zhang and Wei, 2012). Diverse researches using artificial intelligence and/or automatic control systems have been carried out to minimize the energy consumption of HVAC system (Giretti et al., 2012; Zhang and Wei, 2012; Shi et al., 2014). However, the most operation of subway systems does not function with the mode (e.g., fan frequency) conversion to save energy (Shi et al., 2014).

Therefore, in this study, we developed and applied a novel control system (self-control system) equipped with a hybrid activated carbon bed (HACB) to save energy and remove NO_2 from the platform of underground subway station. The removal efficiency (RE) and lifetime of the HACB by control parameters such as superficial gas velocity and relative humidity were investigated. The variation in the RE of NO_2 using the self-control system in the HVAC system was also tested. In addition, economical and energy efficiency according to operating conditions of the system were evaluated.

2. Experimental methods

2.1. Experiment site

The Seoul subway system consists of line 1–9 and occupies more than 30% of transportation services. The number of total stations and length of operation are 311 and 331.9 km, respectively. Seven million people use the subway on a daily basis (Seoul Metro Transportation Center, http://www.seoulmetro.co.kr). We selected Daecheong station in line 3 as an experiment site for this study.

Fig. S1 of Supporting Information shows the schematic of Daecheong station. The total area of station is 8115 m^2 and the length of platform is 205 m (Seoul Metro Transportation Center, http://www.seoulmetro.co.kr). There are eight exits. Furthermore, there are four HVAC systems, which were not equipped with air filters for removal of gaseous compounds (NO_2, VOC, etc.), to supply fresh air into the platform and waiting room. Platform screen doors were set up to interrupt the mixing of air between the platform and tunnel. The number of trains for a day is approximately 400 (Seoul Metro Transportation Center, http://www.seoulmetro.co.kr).

2.2. System setup

To construct a HACB, the optimal hybrid activated carbon ratio was deducted via a lab-scale experiment (Son et al., 2011). On the basis of the pressure drop and the RE of NO_2, the optimum ratio of constructed activated carbon (specific surface area: 648 m^2/g) and granular activated carbon (866 m^2/g) was determined to be 2:1. More detailed information for physical properties of a these activated carbons is presented in Table 1. The thickness of HACB was 30 mm. A self-control system equipped with 15 panel-type HACBs were set up in a subway HVAC system (Fig. 2(a) in Supporting Information). We designed the self-control system that can control the angle of the HACBs according to changing the NO_2 concentration. To do this, the inverter frequency was controlled to equal the superficial gas velocity when the hybrid activated carbon bed was set at the angles of 45° (horizontal direction on air flow; Fig. 2(b) in Supporting Information) and 90° (vertical direction on air flow; Fig. 2(c) in Supporting Information). The power consumption by an elapsed time was measured using a watt-hour meter (AMSYS, 220V 60 Hz, Korea) considering the cost benefit.

2.3. Sampling

All experiments were carried out at Daecheong station for eight months (from September 2011 to May 2012). Fig. 1 shows a schematic of the HACB installed in a HVAC system and sampling sites to measure the NO_2 concentration. To estimate the RE of NO_2 of the HACB installed in the HVAC system, NO_2 concentrations at a ventilation hole (sampling #1) and platform (sampling #4) were measured before and after installation of the HACB. For this, NOx analyzers (Model 32i, Thermo Scientific, USA) were each set up in the ventilation hole and platform. The NO_2 concentration by these analyzers was obtained every 40 s and the mean value of one hour was then used to compare levels of NO_2 according to sampling sites. Particularly, the analyzer installed in the platform was positioned about 1 m away from the air exhaust hole of the platform to avoid the effects of direct air flow. Additionally, NO_2 concentrations before (sampling #2) and after (sampling #3) the HACB were measured to evaluate the direct RE of NO_2 by the HACB. A suction pump (flow rate: 5 L/min) was utilized in the subway HVAC system to draw air before and after the HACB. A dust filter (H12, EGIS, Korea) was installed on the HACB to prevent the inflow of fluttering powder generated by the activated carbon. Besides, a thermo-hygrometer (K22L0, Wisesensing, Korea) was used to investigate the effect of relative humidity on the HACB. Additionally, NO_2 concentrations and relative humidity in ambient air were obtained from the nearest air monitoring station (AIRKOREA operated by Ministry of Environment in Korea).

In the HVAC system, the RE of NO_2 and breakthrough point of the HACB would be depended on superficial gas velocity (m/s). Therefore, we controlled the inverter frequency (20, 30, and 40 Hz) to switch superficial gas velocity. An anemometer (LV110, KIMO,