CFD기반 공공시설 내 NO2 저감 장치 위치에 따른 농도분석 및 노출평가

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Abstract

In 2021, the average NO2 concentration measured near roads was found to be 0.034 ppm, exceeding the ambient air quality standards and posing a threat to the respiratory health of citizens who frequent public facilities such as bus stops. In this study, we developed a system to reduce NO2 by downsizing the scrubbers typically used in chemical processes and applying them to bus stops. We conducted a case study using Computational Fluid Dynamics (CFD) to investigate the effectiveness of NO2 reduction based on the placement of air purification devices in various bus stop scenarios. Exposure assessments based on NO2 concentrations within the breathing zone were performed, with the breathing zone defined considering average height. Analyzing the results using the Added Health Risk (AR) and Exposure Reduction Effectiveness (ERE) assessment methods, we found that placing the air purification devices on the right side resulted in a decrease of AR by 0.11% points and an increase of ERE by 6.35% points, leading to the most significant reduction in NO2 concentration within the breathing zone.

Introduction

The elevated levels of NO2, measured at 0.034 ppm near roadways in 2021, pose a significant threat to public health, particularly for individuals frequenting areas like bus stops. To mitigate this risk, we developed a novel system that miniaturizes traditional scrubbers used in chemical processes and applies them to bus stop environments for NO2 reduction. Through Computational Fluid Dynamics (CFD) analysis, we investigated the efficacy of various air purification device placements in reducing NO2 concentrations. Our study focuses on assessing the exposure to NO2 within the breathing zone, considering average height. Utilizing the Added Health Risk (AR) and Exposure Reduction Effectiveness (ERE) evaluation methods, our findings highlight optimal placement strategies to achieve the most substantial reduction in NO2 levels within bus stop environments.

CFD Modeling

- The RNG k-epsilon turbulence model has been reported to accurately predict the distribution of contaminants in preliminary studies on air purification systems and ventilation efficiency. The equations are as follows.
- The actual numerical values of the bus stop located at Ulsan Hyomun Intersection and Duckha market were applied to the modeling, with an open zone representing the entrance and exit (Figure 1).
- In this study, the breathing zone for Ulsan elementary school students to adults was considered and set in the range of 1.2 to 1.8 meters (Figure 2).
- The modeling scenario considered the worst-case scenario where the wind blows at 2 m/s in the forward direction towards the bus stop (Table 1).

Mathematical model

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial(x_i)}=\frac{\partial}{\partial x_j}\left[\alpha_k\mu_{eff}\frac{\partial\kappa}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_m+S_k$$

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial(x_i)}=\frac{\partial}{\partial x_j}\left[\alpha_\varepsilon\mu_{eff}\frac{\partial\varepsilon}{\partial x_j}\right]+G_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}C_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}-R_\varepsilon+S_\varepsilon$$

G_k: Generation of turbulence kinetic energy due to velocity gradients
Y_M: Generation of turbulence kinetic energy due to buoyancy
G_b: Contribution of compressible turbulence-induced fluctuating dilatation to the overall dissipation rate
α_k, α_ε: Inverse turbulent Prandtl numbers for k and ε
S_k, S_ε: User-defined source terms

Geometry & Boundary condition

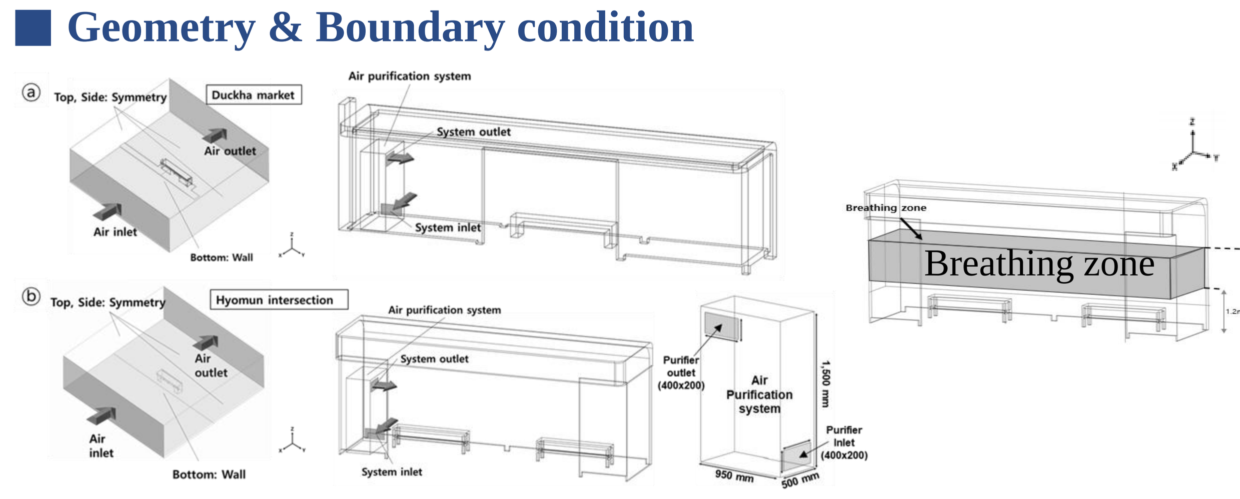

Figure 1. Geometry & Boundary condition

Table 1. Boundary conditions

Bus stop	Boundary Configuration	Nature of Boundary	Boundary Condition Details
ⓐ Deokha market	Air inlet	Velocity inlet	Velocity=2 m/s, NO_2 mass fraction=3.4e-8, SO_2 mass fraction=4.55e-9,
	Air outlet	Pressure outlet	Gauge pressure=0 Pa
	Top, Side	Symmetry	-
	Bottom	Wall	-
	Air purification system inlet (AP_{in})	Velocity inlet	Velocity=2.0833 m/s, NO_2 mass fraction $=AP_{out(NO2)}\cdot 0.61$, SO_2 mass fraction $=AP_{out(SO2)}\cdot 0.01$
	Air purification system outlet	Pressure outlet	Gauge pressure=0 Pa
ⓑ Hyomun intersection	Air inlet	Velocity inlet	Velocity=2 m/s, NO_2 mass fraction=2.57e-8, SO_2 mass fraction=5.77e-9
	Air outlet	Pressure outlet	Gauge pressure=0 Pa
	Top, Side	Symmetry	-
	Bottom	Wall	-
	Air purification system inlet (AP_{in})	Velocity inlet	Velocity=2.0833 m/s, NO_2 mass fraction $=AP_{out(NO2)}\cdot 0.61$, SO_2 mass fraction $=AP_{out(SO2)}\cdot 0.01$
	Purification system outlet	Pressure outlet	Gauge pressure=0 Pa

- The Added health Risk (AR) is an air quality index developed to assess the impact on human health according to changes in the concentration of air pollutants. A lower AR value indicates a lower level of air pollution.
- AR is expressed by the following equation:

$$AR_P=\left[\exp(\beta_P C_{pt})-1\right]100\%$$

C_{pt}: $3-h$ moving average concentration $\left(\frac{\mu g}{m^3}\right)$ of pollutant p at time t
β_p: a regression coefficient in units of $\left(\frac{\mu g}{m^3}\right)^{-1}$ of pollutant p.

$$ERE=1-\frac{\int_0^T\bar{C}dt}{\int_0^T\bar{C}_{ref}dt}$$

- $\bar{C}$ represents the average concentration of NO2 in the breathing zone at time T when an air purification system is in use (measured in mg/m³ or number of particles/m³). On the other hand, $\bar{C}_{ref}$ denotes the concentration of NO2 in the breathing zone at time T without the use of an air purification system (measured in mg/m³ or number of particles/m³)

Result & Discussion

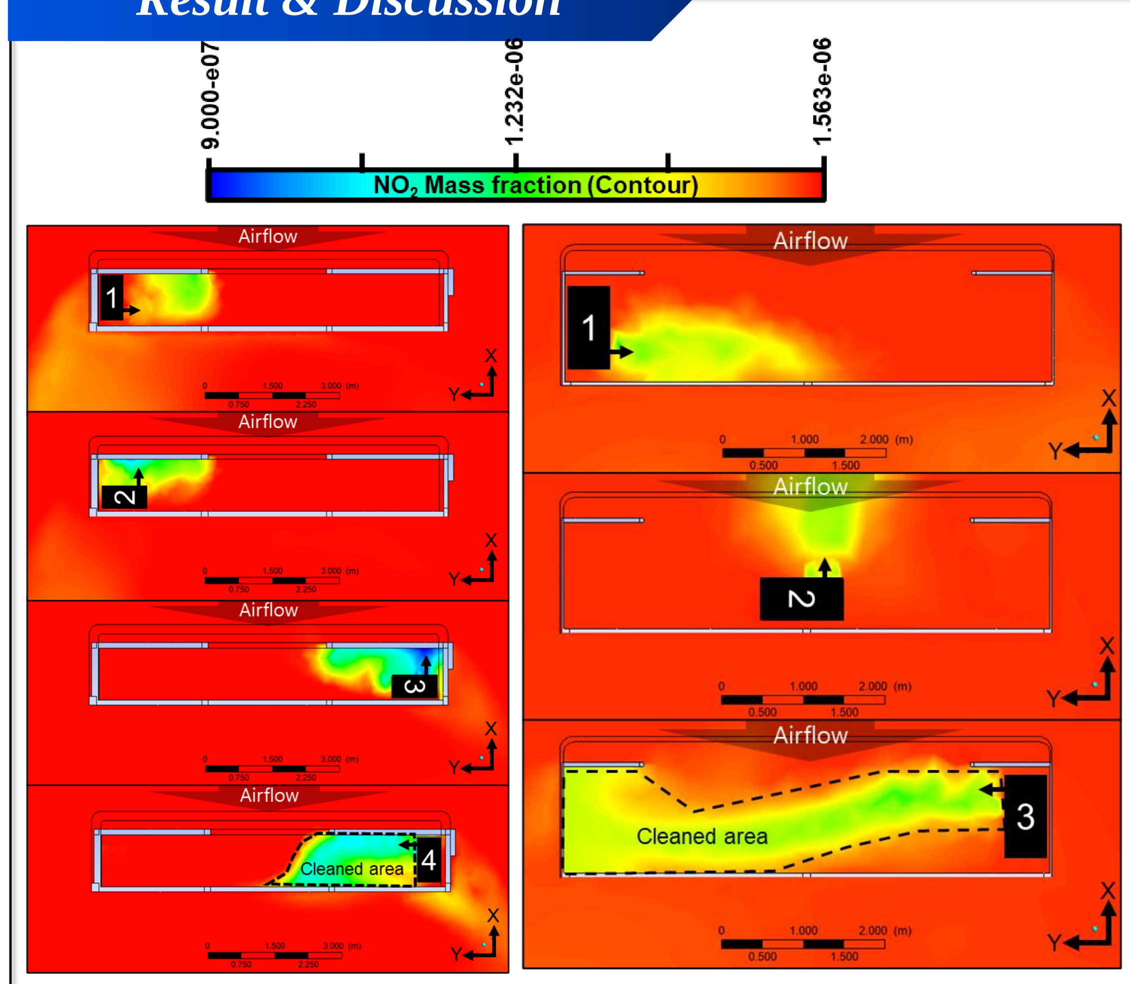

Figure 2. Comparison of NO2 concentration contour inside ⓐ Duckha Market (left) and ⓑ Hyomun intersection (right) bus stop (Z=1.5 m)

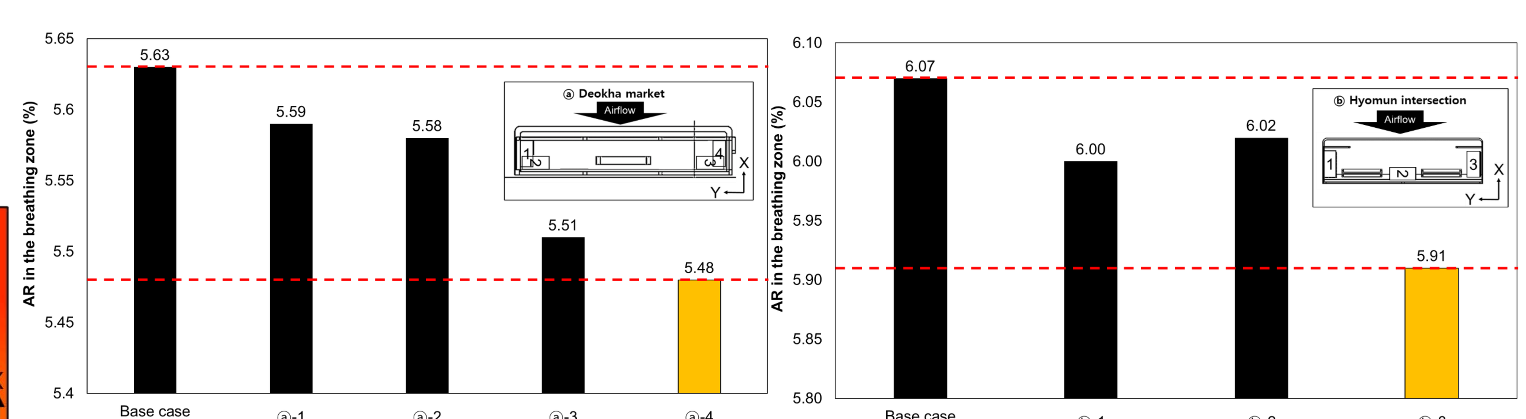

Figure 3. the AR results for the placement of air purification systems at the bus stops of Duckha Market and Hyomun Intersection.

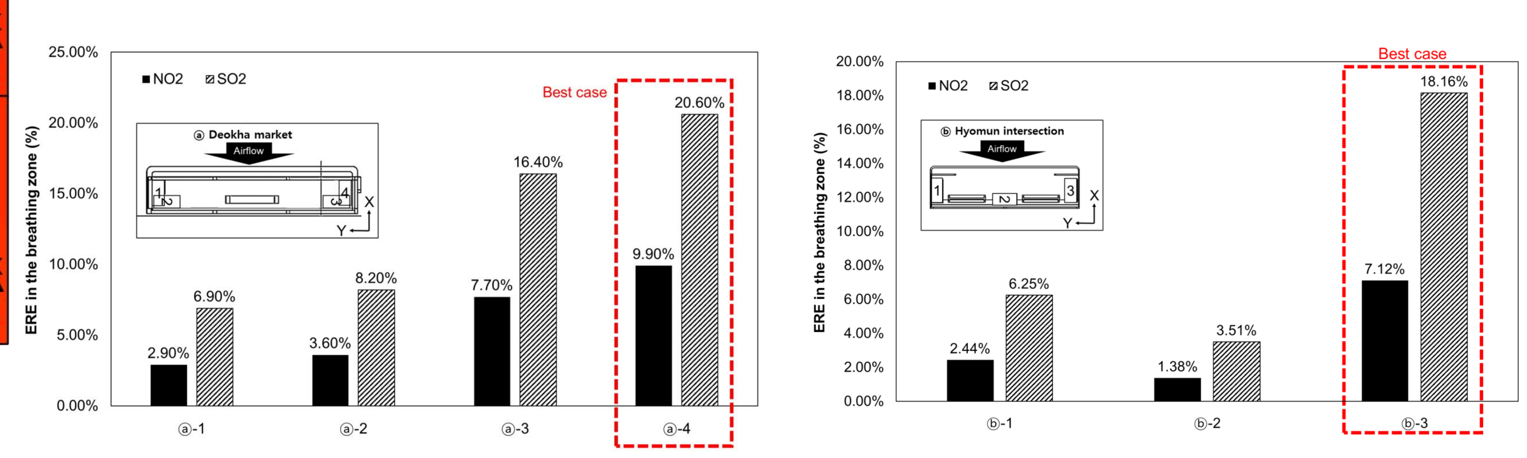

Figure 4. depicts the ERE results for the placement of air purification systems at the bus stops of Duckha Market and Hyomun Intersection.

- The Figure 2 illustrates the distribution of NO2 concentrations at the bus stops located at Hyomun Intersection and Duckha Market. In both cases, when positioned on the right side, a cleaned area is formed, blocking external airflow and maintaining low concentrations of yellow and green hues overall.
- Figure 3 depicts the AR values for four scenarios with air purification systems at the Duckha market bus stop.
- The base scenario has an AR of 5.63, while scenarios ⓐ-1 to ⓐ-4 show varying AR values, with the system at ⓐ-1 resulting in a reduction to 5.59. The analysis suggests strategic placement of purification systems can mitigate health risks in urban areas.
- the AR associated with the placement of air purification system in three different cases at the Hyomun Intersection bus stop. The base case represents the absence of air purification system, with an AR value of 6.07% (Figure 3).
- Considering the ERE values and sensitivity per breathing zone volume, the optimal scenario for air pollutant removal at bus stop ⓐ achieves an ERE of 15.25% with a volume of approximately 8.64 m3, resulting in an ERE sensitivity of 1.20% per cubic meter (Figure 4).

Conclusion

- In conclusion, the study showcases the efficacy of downsized scrubbers applied to bus stops for reducing NO2 concentrations.
- Strategic placement resulted in notable improvements, with reductions in Added Health Risk (AR) values from 6.07% in the base case to 5.59% in the optimal scenario.
- Moreover, the optimal scenario at bus stop ⓐ achieved an Exposure Reduction Effectiveness (ERE) of 15.25% with a sensitivity of 1.20% per cubic meter, highlighting the significance of proper air purification system positioning in mitigating health risks associated with elevated NO2 levels near public facilities.

Reference

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[2] Md. Shakhaoat Hossain., et al. "Combined effects of increased O_3 and reduced NO_2 concentrations on short-term air pollution health risks in Hong Kong", Environmental Pollution 270(2021): 116280