Purifying City Air in Densely Urban Environment

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ABSTRACT

Worsening air pollution poses a large and growing public health problem. More than 80% of people currently live in urban areas with air quality levels that exceed WHO particulate matter (PM) concentration limits. They are subjected to a higher risk of cardiac arrests, peripheral vascular disease (PVD), lung cancer, respiratory diseases, and asthma. Poor air quality is mainly caused by rapid urbanisation and industrialisation, which require high energy consumption and transportation flow. Air pollutants are emitted from power plants and vehicles, and are trapped in the built environment, to which people on the street are exposed all the time.

In view of the pressing need to combat roadside air pollution, Arup and Sino Green have developed a novel, patented system called the City Air Purification System (CAPS) that won the second prize of the Construction Industry Council (CIC) Innovation Award 2015. The prototype, a stand-alone system with a ventilation system that filters out pollutants and purifies air for pedestrians in proximity to the system, has been tested in Hong Kong and Beijing and has effectively reduced air pollutant (PM2.5 and PM10) concentration within the system by 30% to 70% under various ambient conditions. This paper focuses on the simulations and analysis showing the improvement of roadside air quality resulting from CAPS when it is incorporated into buildings located in a busy district in Hong Kong.

Keywords: *air pollution, purification, roadside health, public transportation*

1. INTRODUCTION

In many Asian cities, pollutants emitted from vehicles permeate through the crowded city roads, poor air quality has become a threat to pedestrians or roadside stores. Air pollutants emitted from vehicles in densely-built cities such as Hong Kong, where streets are narrow and bounded between high-rise buildings, cannot be naturally circulated and diffused to the atmosphere; instead, they accumulate at the bottom of the street due to the Street Canyon Effect. This poses health problems to urban residents using nearby pedestrian walkways. Chinese cities like Beijing and Shanghai share similar difficulties in maintaining acceptable air quality level on the street. On a high-pollution day in Beijing, the roadside monitor could record over 600 Air Quality Index (AQI), which is twice the index level considered hazardous to human health. In the 2016 Environmental Performance Index (EPI) developed by Yale University and Columbia University, China, India, Myanmar, South Korea, and Vietnam ranked 170-179 out of 180 countries in the air quality category. Other than pollutants emitted from vehicles, smoke coming out from chimneys of coal power plants and factories worsen air quality by raising the ambient pollution level. If the layer of heavy pollution and the ambient pollution level are not treated and continue accumulating, the risk of respiratory disease of pedestrians would increase.

The main purpose of the CAPS innovation is to develop a solution that could mitigate major air ventilation difficulties in urban areas with the Street Canyon Effect, and to study the feasibility of different roadside ventilation systems for improving roadside air quality.

1.1. Street canyon effect in built environment

One main difficulty in ensuring natural ventilation in urban areas is the massive number of high-rise buildings on narrow streets and roads. Pollutants emitted by heavy traffic do not have sufficient energy to rise up to high attitudes to escape the containment of surrounding buildings. As a result, air quality worsens as pollutants like particulate matters and nitrogen oxides accumulate at the pedestrian level of the street canyon. The geometry of the street canyon, along with the wind direction and wind speed, are the major parameters that affect the air pollution's dispersion in the area. In a dense and compact cosmopolitan city like Hong Kong with population of over 7 million, the aspect ratio between the building height and the street width ranges from 3 to number larger than 10. A study showed that an increase of 30% to 80% on the retention time of pollutants in the street canyon was due to the air ventilation impact from the high-rise buildings and its 'wall effect'. The air pollution problem in a mega city like Beijing with a population of over 16 million, which has an aspect ratio of 2 to 4.5, is also affected by the effect. Beijing's building development is comparatively less compact, but it faces more severe ambient air pollution in general. Hong Kong and Beijing have different characteristics in terms of city development and environmental conditions, but both are affected by air pollution due to the Street Canyon Effect.

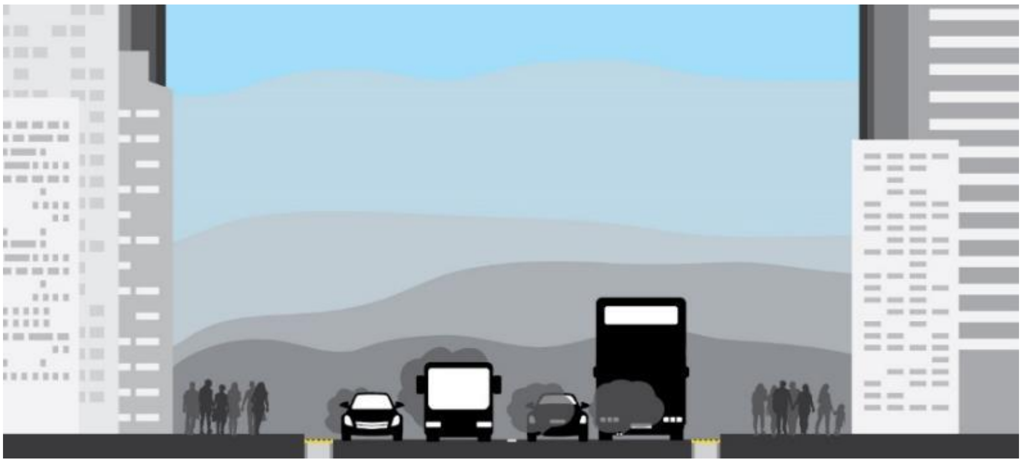

Figure 1: A Typical street canyon in an urban area

Street Canyon Effect, as shown in Figure 1, represents the inability of normal wind channel to flow into and ventilate the road and the formation of a primary vortex of wind circulating inside the area between buildings. Both characteristics of the Street Canyon Effect reduce the chance for pollutants to escape; as a result, they accumulate to a hazardous level of concentration, which is harmful to human health. Over-exposure to highly polluted air would lead to a greater risk of allergies and respiratory diseases.

2. CITY AIR PURIFICATION SYSTEM (CAPS)

2.1 Engineering design

To mitigate the immediate and pressing air pollution problem due to the Street Canyon Effect in cities like Hong Kong and Beijing, Arup and Sino Green developed a patented innovation called the City Air Purification System (CAPS). Since its debut in March 2015, CAPS has gained attention from international and professional media, including: Forbes, Bloomberg, The Guardian, China Daily, Architect Magazine and Global Construction Review. The main goal of the innovation is to provide purified air for pedestrians through a ventilation system that filters out pollutants and generates cleaner air in proximity to the system.

Figure 2: City air purification system (CAPS)

The innovation, illustrated in Figure 2, was designed with fluid mechanic principles so that it could build up an air curtain and a positive pressure to create a cleaner environment. The polluted air is drawn into CAPS at a low level, which is then filtered and recirculated to improve the air quality of the space inside CAPS. Purified air is supplied at the top of CAPS at a high velocity that serves as an air curtain, or an invisible barrier, isolating the occupied space inside CAPS from the adjacent polluted ambient. The purified air emitted through the fan chamber creates a positive pressure inside CAPS and pushes the polluted gas away. CAPS is equipped with a quiet and high energy efficiency fan and a High Efficiency Particulate Arrestance (HEPA)-type (medical-level) filter that is capable of filtering away up to 95% of PM2.5 and larger suspended particulate matters (PM) in the ambient air. With CAPS, people who are standing or waiting in the outdoor polluted roadside environment will be able to breathe in cleaner air.

2.2 Engineering simulation

Based on the design of CAPS, a computational fluid dynamics (CFD) model was developed to study the effectiveness, practicability, usability, and flexibility of different design solutions. Furthermore, the CFD modelling technique was used to optimise the system operating conditions that maximise the overall filtration effectiveness, while minimising energy consumption.

In the CFD model, a wide range of different scenarios and operating conditions were simulated and investigated. The scenarios covered various system variability and ambient factors such as external wind and background ambient pollution level at the system and city-wide levels. Sample results, shown in Figure 3, verify that CAPS is effective in maintaining a cleaner air zone (blue in the Figure) and to keep away from the surrounding pollution (green to red in the Figure). Under different ambient conditions, simulations were carried out to investigate the impact of different system operating parameters on overall filtration effectiveness and fan requirement. Using the results, the optimised system operation in terms of air pollutant level inside the system area, air balance of the air delivery system, and fan operating speed were determined.

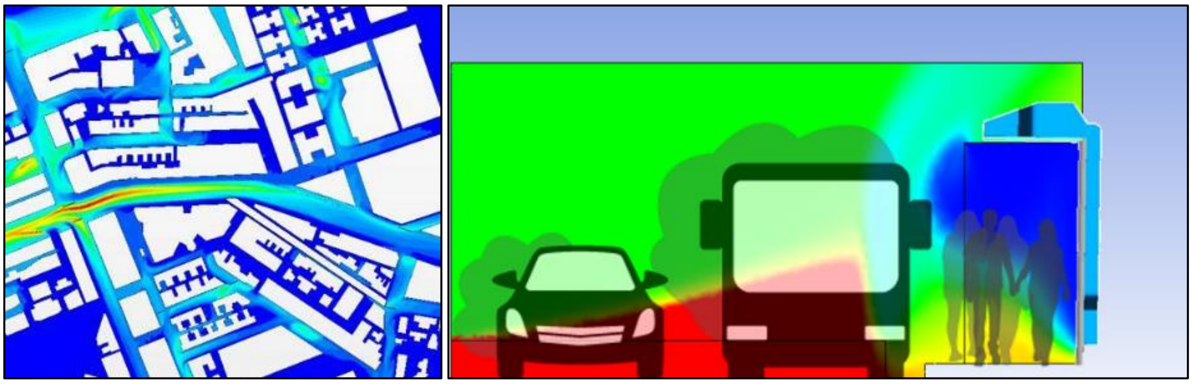

Figure 3: City-wide CFD simulation (left) and system CFD simulation (right)

2.3 Roadside testing

To demonstrate the effectiveness of the system, CAPS was first placed in Wan Chai, Hong Kong for two months and then relocated to Tsinghua University in Haidian district of Beijing. During the demonstration, continuous performance data logging and on-site manual measurements were conducted. The testing results showed that CAPS is able to provide clean air within its covered area, which achieved an air quality that complies with the World Health Organisation (WHO)'s PM2.5 guideline values.

Roadside testing in Hong Kong was conducted from March to May 2015 to analyse the real system performance with respect to the ambient air quality data inside the system area. CAPS was installed in Queen's Road East in Wan Chai, one of the busiest districts in Hong Kong situated between two official government roadside air monitoring stations located in Central and Causeway Bay. The collected data were compared to the published data. After verifying performance in Hong Kong, CAPS was relocated to Beijing for roadside testing in different environmental conditions from July 2015 onward. A similar approach, including continuous data logging and manual on-site measurements, was adopted. Similarly, the collected data inside CAPS were compared to the ambient data in Beijing.

Different system operation settings were tested using a set of testing protocol for on-site measurements. After the air quality inside the system was measured, the fan speed and the air delivery angle were adjusted for studying different design scenarios. The maximum power for the system was 13A and it cost HK$16 per day for continuous operation. The measurement was also used to identify the filter conditions. Owing to particle blockage and aging of the filter, filter performance deteriorates when the flow rate reduces. The measurement results provided alerts for when to clean or replace the filtration system. Depending on the roadside conditions, the filter is expected to be replaced every two to six months. Further testing details can be found in.

Based on the collected data in Hong Kong and Beijing, a correlation analysis was conducted using measured data from roadside testing and simulated data from the CFD model. As shown in Figure 4, results showed that the simulation model is able to predict the real situation with a difference of less than 10%. Based on the current data analysis, CAPS is capable to reduce the PM2.5 concentrations by 30%-70%, depending on the ambient pollution level.

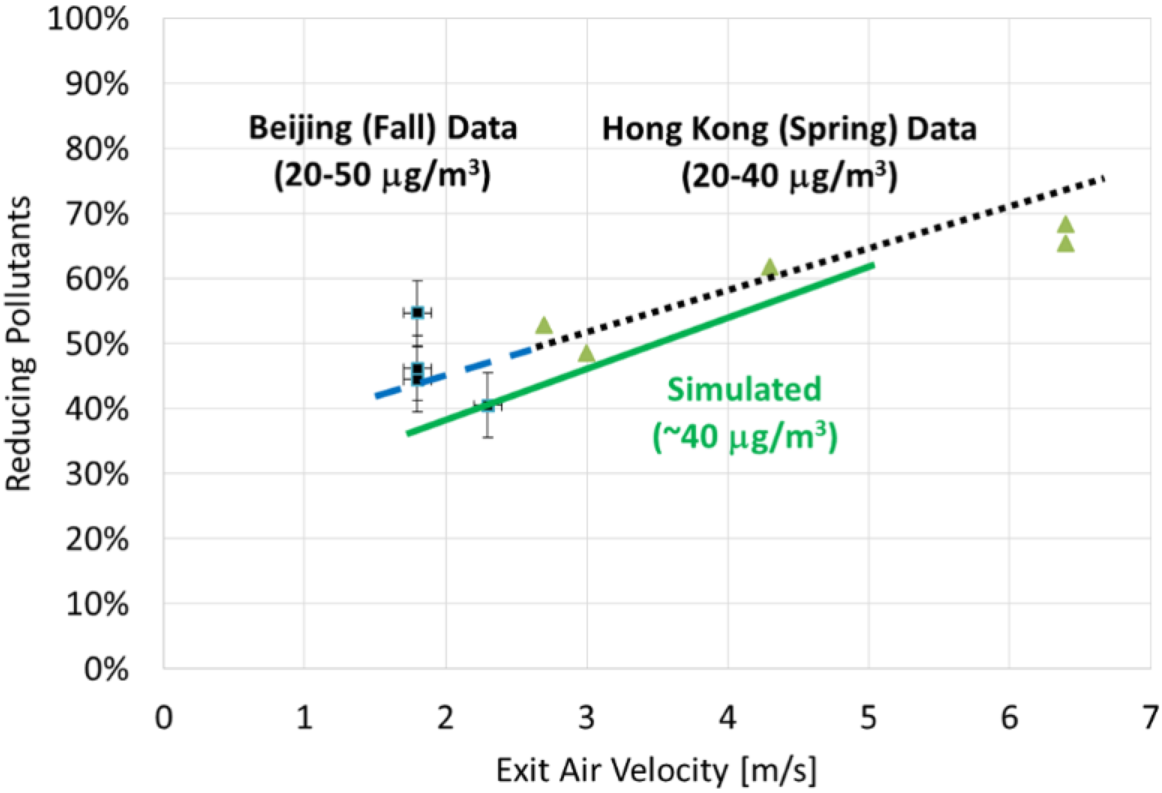

Figure 4: Correlation results between measured and simulated data for Hong Kong and Beijing roadside testing

2.4 Economic benefits

Many researchers have also attempted to quantify the economic cost due to the air pollution problem. One such analysis for Hong Kong case is done by Hedley Environmental Index. Accounting for deaths, hospital visits, and productivity loss, the Hedley Environmental Index estimated about HK$41 billion economic losses due to pollution-related health problems in 2013.

If 200 CAPS are implemented in the 10 districts most impacted by poor air quality, as shown in Figure 5 (base map from [18]), CAPS would be saving HK$330 million per year for Hong Kong, which is four times of the social benefit relative to the initial cost of the system. The benefit is achievable even with the assumption of only about 30 minutes of protection inside CAPS per day while waiting for the traffic, and the benefit can be observed by 60% of the entire population in Hong Kong in those mentioned 10 districts (1. Central & Western, 2. Wan Chai, 3. Eastern, 4. Kwun Tong, 5. Kowloon City, 6. Yau Tsim Mong, 7. Sham Shui Po, 8. Kwai Tsing, 9. Tuen Mun, and 10. Yuen Long).

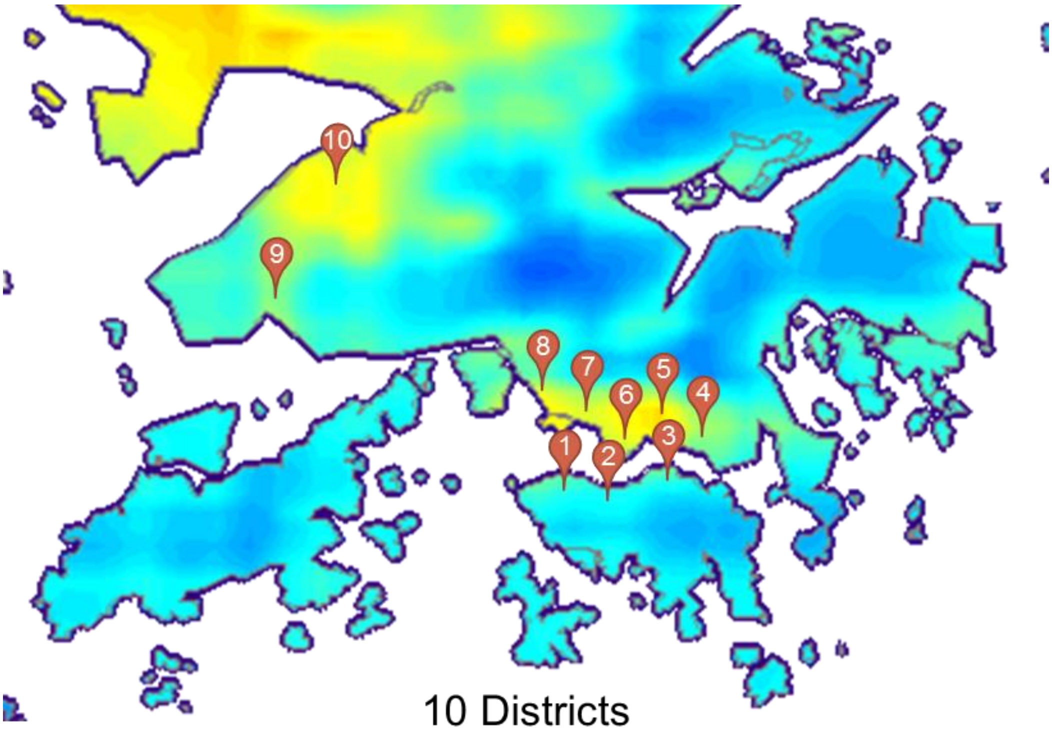

Figure 5: Most polluted districts in Hong Kong

3. CONCLUSION AND FURTHER DEVELOPMENT

Based on the analysis and tested data, the CAPS can reduce the air pollution level of PM2.5 by about 50% on average under various ambient pollution levels. Figure 6 shows CAPS's demonstration model in Hong Kong and Beijing during the testing period.

Figure 6: Demonstration in Hong Kong (left) and Beijing (right)

CAPS has wide ramifications and applications. For instance, given that Hong Kong has a well-established public transport network, the system can be adopted for bus shelters, tram stations, and other applications to improve air quality. The patent covers different forms of CAPS, including building canopy, outdoor kiosk, and central underground filtration system. For example, buildings canopy could supply fresh air to the pedestrian level and keep clean air recirculated right in front of the building entrance to improve the overall air quality around the area. The ideas can work for new designs; it is also possible to retrofit existing bus shelters and buildings. With such appealing performance data, CAPS could be produced in mass and applied in major Asia cities, such as Beijing, Shanghai, Ho Chi Ming City, etc., all of which suffer from severe air pollution problems.

As the measured data reveal that CAPS can effectively reduce pollutant levels to a recommended level of PM2.5 according to WHO standards, CAPS can be developed into next-generation systems in the future. The major objective of developing the next-generation systems is to further improve its effectiveness, so as to make it low-carbon or even zero-carbon, in order to improve air quality inside the system area.

4. ACKNOWLEDGEMENT

The patented City Air Purification System (CAPS) was developed by Arup and Sino Green.

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