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Improving air quality in high-density cities by understanding the relationship between air pollutant dispersion and urban morphologies

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ABSTRACT

In high-density megacities, air pollution has a higher impact on public health than cities of lower population density. Apart from higher pollution emissions due to human activities in densely populated street canyons, stagnated air flow due to closely packed tall buildings means lower dispersion potential. The coupled result leads to frequent reports of high air pollution indexes at street-side stations in Hong Kong. High-density urban morphologies need to be carefully designed to lessen the ill effects of high density urban living. This study addresses the knowledge-gap between planning and design principles and air pollution dispersion potentials in high density cities. The air ventilation assessment for projects in high-density Hong Kong is advanced to include air pollutant dispersion issues. The methods in this study are CFD simulation and parametric study. The SST $\kappa-\omega$ model is adopted after balancing the accuracy and computational cost in the comparative study. Urban-scale parametric studies are conducted to clarify the effects of urban permeability and building geometries on air pollution dispersion, for both the outdoor pedestrian environment and the indoor environment in the roadside buildings. Given the finite land resources in high-density cities and the numerous planning and design restrictions for development projects, the effectiveness of mitigation strategies is evaluated to optimize the benefits. A real urban case study is finally conducted to demonstrate that the suggested design principles from the parametric study are feasible in the practical high density urban design.

1. Introduction

1.1. Background

People living in high-density cities suffer from both short and long term exposure to ambient air pollution. This causes severe health problems [1–3]. The risk of air pollution is relatively low to individual health but is considerably higher to public health [3]. Understanding the problem from the urban and city scale is therefore paramount.

Emissions from motor vehicles contribute to air pollution in urban areas, particularly at street canyon levels. The European Environment Agency (EEA) [2] has reported seven types of pollutants that people are exposed to, namely, particulate matter (PM), ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), heavy metals, as well as benzene (C_6H_6), and benzopyrene (BaP). All of these pollutants are primarily or secondarily related to road traffic (fossil fuel combustion). The World Health Organization (WHO) [1] has therefore explicitly recommended the concentration limits for various air pollutants such as O_3 and NO_2.

To decrease traffic pollution, an improved vehicle emission control program has been implemented in Hong Kong by the Hong Kong SAR Government. Nonetheless, the roadside concentration of NO_2 continues to increase [4]. Similar findings are also being reported in Europe by EEA [2]. High hourly, daily, and annual average concentrations of NO_2 have been recorded at the road-side stations in the Central, Causeway Bay, and Mong Kok areas in Hong Kong. Air pollution far exceeds the limits recommended by the WHO [4]. The three areas are high-density metropolitan areas and traffic hotspots. As shown in Fig. 1, vehicles crowd the streets of high-density urban areas in Hong Kong. The reported higher concentration of NO_2 is the result of the larger NO_2 percentage in total traffic emissions [2,5] and of poorer urban air ventilation in high-

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Fig. 1. Vehicle fleets in the deep street canyons of Mong Kok and Wan Chai in Hong Kong; high concentration of NO_2 is frequently measured at the roadside stations in the areas.

density urban areas [6,7]. The bulky building blocks, compacted urban volumes and very limited open spaces seriously block the pollutant dispersion in these deep street canyons [8,9]. Therefore, apart from having control measures to decrease vehicle emissions, understanding pollutant dispersion as related to the urban planning and design mechanism is necessary in order to guide policymakers, planners, and architects in making better evidence-based decisions.

1.2. Literature review

Several studies on urban climate in the past decades have focused on air quality in the street canyons [10]. In some studies, the "car-chasing" experiment and tunnel testing have been conducted [11,12] to determine the real-world traffic emission factors of particles and gaseous pollutants, and to evaluate the chemical compositions of emissions from different vehicles. These studies provided important information for evaluating the effects of different pollutants on public health, and to assist in drawing up guidelines for policymakers to implement transportation control measures. These studies are also important references as the input boundary conditions for pollutant dispersion modeling.

Computational fluid dynamics (CFD) studies in different scales have been conducted by researchers to identify the dispersion phenomenon in street canyons. Pollutant dispersion has been investigated in idealized street canyons with a point or line emission source with [13,14] or without chemical reaction [9,15–18]. Researches on isothermal and non-isothermal street canyons, in which the effects of convective and turbulent mass fluxes on dispersion were studied, have been reported [19,20]. These studies have provided important information on pollutant dispersion patterns, as well as on the relationship among wind velocities, turbulence intensities, and pollutant dispersion. By cross-comparing the modeling results with wind tunnel experiment data, these studies have also evaluated the performances of their dispersion and turbulence models.

Urban microclimate and air quality can be seen both as the consequence and as the prerequisite of urban planning and design activities. Therefore, the reciprocal relationship between them requires research on the environmental sensitivity of urban planning and design, in order to positively address their negative consequences on urban air quality. Mirzaei and Haghighat [21] provided a systematic approach to quantify the outside environment in the street canyon. Huang et al. [20] studied an actual urban case of mid-density layouts. Hang et al. [8] conducted a study on the effects of varying building heights on street level air pollutant dispersion and Eefents et al. [22] reported the effects of canyon indicators such as Sky View Factor (SVF) on the concentration of NO and NO_x. Buccolieri et al. [23] clarified the influence of the building packing density on the pollutant concentration. Richmond-Bryant [24] related the fluid properties and canyon geometries, such as the Reynolds number and canyon height, with air pollutant retention by field measurement data at Manhattan and Oklahoma. However, the direct understandings for design strategies behind a decrease in pollutant concentration through urban morphological mechanisms, particularly for high-density cities, remains little known. Further parametric studies are needed to extend the study findings for practical design applications. Bridging the knowledge gap between high-density urban design and air pollutant dispersion mechanisms in the urban street canyons is necessary to provide guidance for planners, designers and policymakers.

1.3. Objectives

The Severe Acute Respiratory Syndrome (SARS) episode in 2003 triggered the Air Ventilation Assessment (AVA) study in Hong Kong. Since 2006, AVA has been implemented as a prerequisite for urban development and old-district redevelopment [25]. Major government projects have been required to conduct an AVA by following the Technical Circular No. 1/06 guideline. Furthermore, the "Sustainable Building Design (SBD) Guidelines (APP-152)" have also been drawn up by the Hong Kong Government. These allow architects to evaluate the effects of their proposed buildings on the surrounding wind environments, and to enhance urban environmental design by prescriptively applying three user-friendly strategies: building setback, building separation, and greenery [26].

This study builds on the previous work [27] by conducting parametric studies to statistically evaluate and further develop the efficacy of the AVA TC-1/06 guidelines and the SBD's APP-152 guidelines with regard to air pollutant dispersion. The study aims to provide important and sufficiently accurate insights at the beginning stage of the design practice. These insights are helpful to avoid the mistakes that cannot be easily corrected at the late stages of the design practice. The results of this study are intended to facilitate a paradigm shift from the typical experience-based ways of designing and planning to a more scientific, evidence-based process of decision making, which is necessary to cope with the needs of designing high density cities [28].

This study firstly evaluates the performance of both the Reynolds-averaged Navier–Stokes (RANS) and Large Eddy Simulation (LES) models in modeling species transport through a validation study so as to identify the optimal modeling method for the parametric study.