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A procedure to quantify the impact of mitigation techniques on the urban ventilation

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ABSTRACT

Urban heat island (UHI) and urban pollution island (UPI) are recent phenomena caused by human interference in an environment. This interference has an impact on the pedestrian comfort and pollution exposure (PCE). Even though studies have revealed a mutual relation between the UHI and UPI, their interaction is rarely considered in the development of mitigation techniques. That means UHI mitigation technique does not necessarily have similar impact on the pollution exposure and vice versa. For example, the effect of tree planting in a high-rise street canyon can be different from a low-rise one since solar radiation absorption and airflow regime is remarkably different in these street canyons. This implies that street canyon-scale treatment is necessary in order to first clarify the significance of each interaction and, then to apply a proper mitigation strategy to improve the PCE. The existing urban planning guidelines are mainly qualitative and not quantitative, and no procedure has been developed to evaluate the impact of different mitigation technologies on the PCE.

This paper proposes a systematic approach to quantify the level of environmental condition inside a street canyon. This approach is also capable of evaluating the possible advantages of passive and active mitigation strategies using a frequency of occurrence concept. For this purpose, a computational fluid dynamics model is developed to be used to investigate the impact of contributing parameters on the PCE. A case study of a street canyon, located in Montreal, is also considered to investigate the performance of the proposed approach.

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1. Introduction

There are certainly some similarities between ventilating a building in order to provide the required environmental conditions for occupants' thermal comfortable and health, and ventilating an urban canyon to provide the required environmental for the pedestrians' thermal and health. Traditionally, the buildings were designed and constructed to be naturally ventilated as the urban canyon is ventilated these days. As the city planning changed, natural ventilation technique may not be able to provide the required conditions in certain condition and in some buildings thus the building must be ventilated mechanically.

Superstructures and high-rise buildings are becoming part of new cities' landscapes where their large and high exterior surface area impact the air temperature distribution, and this temperature variation induces significant upward or downward thermal convection flow which impact the air pollution in the urban canyon. This phenomenon profoundly influences the pedestrian thermal comfort and health.

Pedestrian thermal comfort strongly depends on the outdoor air temperature, wind velocity, relative humidity, and solar radiation. For example, *lack of evapotranspiration* and vegetation reduces moisture and consequently the level of pedestrian comfort. In addition, construction of street canyons results in *blocking of the prevailing wind breakthrough*. This alteration of airflow regime can inversely increase the pollution concentration level and produce a vulnerable air quality for pedestrians. The airflow regime itself is affected by street canyon geometry [16,17]. Moreover, the street canyon geometry has a direct impact on the shading factor which influences human comfort. An extensive *review paper by* [12] *summarized efforts to investigate and mitigate UHI.*

Many cities recently have provided urban design guidelines and suggested passive mitigation techniques to improve the pedestrian comfort and health. These techniques include: increasing tree planting and vegetation inside urban areas [14], design street canyon and building layout to naturally ventilate urban areas [15], and application of higher-albedo materials [18]. The existing urban planning guidelines are mainly qualitative and not quantitative,

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and a systematic research work has not been done to investigate the impact of these techniques on both improving pedestrian thermal comfort and reduction of air pollution - dealing with urban heat island (UHI) and urban pollution island (UPI) phenomena.

This paper proposes a systematic approach to quantify the impact of heat island and pollution island phenomena in an urban area on the pedestrian thermal comfort and exposure. For this purpose, a Computational Fluid Dynamics (CFD) model is developed to simulate physical interactions around and inside a street canyon. More realistic surface temperature distribution within a street canyon is also modeled with integration of thermal storage and solar radiation models. Therefore, this model first evaluates PCE for a particular street canyon. Then, it predicts the result of possible mitigation strategy on the PCE. The PCE is evaluated in terms of temperature-humidity index (THI) [21], wind comfort index (WCI) [7], and air quality index (AQI) [10]. Finally, air and pollution exchange rate (ACH and PCH) indices are considered in order to demonstrate the air movement and pollution exposure inside the street canyon.

2. Methodology

2.1. Model description

Even though experimental approaches are the most reliable techniques, a continuous and urban-scale implementation of them is not practical or economical. Alternatively, dynamic numerical models have been extensively used due to the recent advancement made in the computer technology. The following section presents a 3-dimensional model to study the environmental condition around a building and quantify the impact of different mitigation technologies on the pedestrians' thermal comfort and exposure.

This model integrates airflow model, turbulence scheme, heat storage model, radiation model, and assigning proper boundary conditions. Moreover, pre-simulation is included in this model to capture the non-uniform distribution of soil and wall temperatures within street canyon. This provides more realistic heat fluxes for each surface to study the environmental condition in the city. Furthermore, performing 3-dimensional CFD simulation includes the effect of streets' intersection in the short street canyons when $L/H < 3$ (L and H are length and height of street canyon, respectively). Navier–Stokes (NS) equation is used as the governing equation to study the physical interactions within the street canyon. The Reynolds-averaged Navier–Stokes (RANS) model is also adapted using $k-\epsilon$ turbulence model.

For airflow simulation, as depicted in Fig. 1, a cuboid domain indicates the field of interest. Appropriate mesh size is first obtained by a mesh size test. In addition to this test, a geometry test is applied to assign appropriate dimensions to the cuboid (L_1–L_5). These tests help to include the physical phenomena inside the model and to reduce the cost of simulations.

Thermal storages within urban areas contribute to the formation of thermal stratification within the street canyon. Part of radiation and convection heat is conducted through the soil, pavements, roof and building wall materials and part is stored within these elements. For a solid surface, the energy balance equation is expressed as below:

$$q_{\text{conduction}} = h_f\left(T_{\text{surface}} - T_{\text{air}}\right) + q_{\text{radiation}} \tag{1}$$

where h_f is the convective heat transfer coefficient, T_{surface} is the surface temperature, T_{air} the air temperature, $q_{\text{radiation}}$ is the incoming solar radiation, and $q_{\text{conduction}}$ denotes the conducted heat transfer rate through the surface. Using the heat-diffusion equation, temperature distribution inside surfaces can be obtained through the numerical models as below:

$$\rho c_p \frac{\partial T}{\partial t} = Q_{gen} + \frac{\partial}{\partial x_j}\left(K\frac{\partial T}{\partial x_j}\right) \tag{2}$$

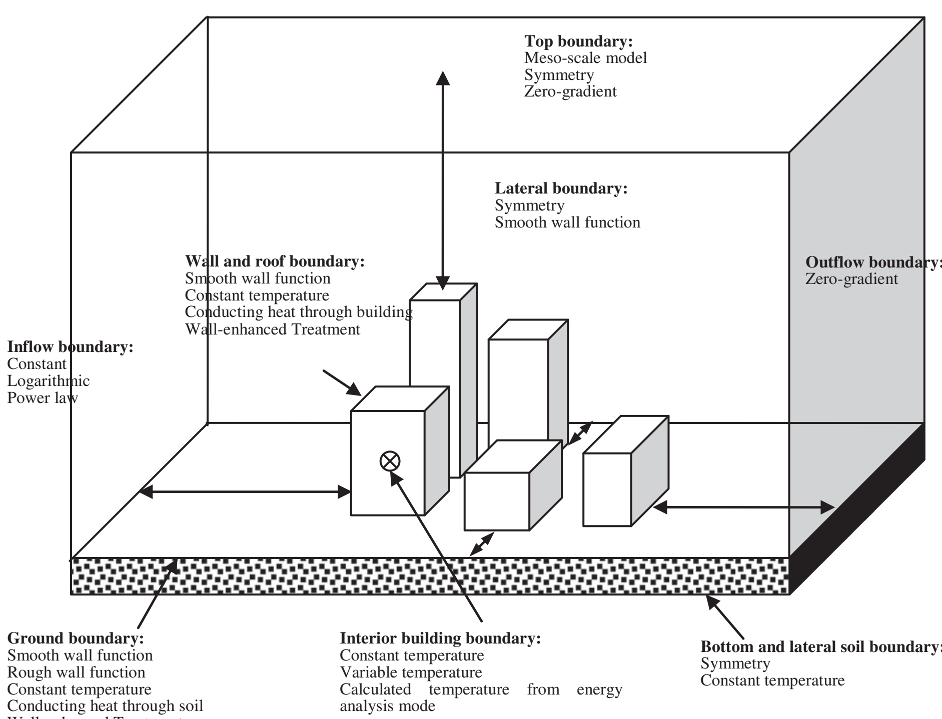

Fig. 1. Domain of study and boundary condition options.

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