Pedestrian Ventilation System:
A Novel Approach to Mitigate Urban Heat Islands

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ABSTRACT

Various urban features and meteorological conditions have been recognized as bases of the Urban Heat Island (UHI) phenomena. Several strategies have also been proposed to mitigate the UHI. However, these strategies are passive countermeasures and are only effective in particular meteorological conditions and urban features.

A new design approach, pedestrian ventilation system (PVS), has been proposed to actively ventilate high-rise building canopies in various stability conditions; stable, neutral, and unstable. According to previous researches, the UHI generally shows more intensity in high-rise building canopies which are mostly existed in high density areas. These areas have typically higher pollution concentration than low-rise residential building areas. This means that pedestrian level air quality in these areas usually reaches hazardous condition in the terms of pollution, temperature, and humidity.

The capability of the PVS to enhance the pedestrian comfort parameters has been studied using CFD simulation. For this purpose, four strategies have been introduced to supply or exhaust air from the building canopies. The results verify that the PVS can generate air movement inside the building canopies and enhance the air velocity as well as the air temperature.

Keywords: Mitigation Technologies, CFD, Air Quality, Ventilation, Building Canopy, Urban Heat Island

Introduction

The number of buildings, the major elements of a city, is increasing with growth of urbanization. For instance each year in the United States, more than 8,100 km² of open space, wildlife habitat, and wetlands are replacing with the buildings (Frej and Anne, 2005). Reported in US and European countries (US Department of Energy, 2006), residential and commercial buildings consume 40 percent of the total energy. USA department of Energy (2007) reported that in 2002, 68 percent of the urban electricity was used by buildings: 51 percent in residential and 49 percent in commercial buildings. This energy consumption contributes to 38 percent of the total amount of carbon dioxide.

This high release of energy in the urban environment significantly changes the urban climate environment as compare with the rural area. This intensifies Urban Heat Island (UHI) phenomena which again increases energy and water consumption within cities as well as the pollution dispersion. During the UHI occurrence and specifically under stable weather condition, air stratification is normally taking place inside building canopies in high-rise down town area which typically have heavy traffic and high release of the anthropogenic heat and pollution (Nakamura and Oke, 1988).

Widespread heat island mitigation strategies (e.g. planting tree, using lower albedo materials in urban structures, inducing sea-breezes and mountain winds through the building canopies, and changing building design and layout) are proposed to reduce the UHI effect and to enhance the outdoor air quality (OAQ). Their performance, however, significantly vary with different urban features and climates. It means that current strategies are passive countermeasures and are only effective in particular meteorological conditions and urban features. However, neither have the ability to actively control air quality parameters inside building canopies.

Moreover, most of these techniques are not applicable for existing buildings. Therefore, it is believed that existing countermeasures are not long-term and efficient solution for heat island problems especially to provide outdoor thermal comfort and to remove urban canopy pollution. Thus, it is necessary to develop an active system to provide a consistent range of air quality indices (i.e. temperature, humidity, pollution, radiation, and velocity,) within building canopies.

Pedestrian Ventilation System

In building canopies mean wind speed is not only an important parameter in air exchange, turbulence also plays a significant role on canopy ventilation, especially in skimming flow (Oke 1988). Kim and Baik (2003) demonstrated the importance of turbulence on the removal of pollutants. On the other hand, it is proven that the created buoyancy by changing the street and the buildings' wall temperature can increase or dominate turbulence inside the canopies (Xie 2005). This usually happens under different atmospheric stability conditions.

Therefore, to control the air movement and pollutant dispersion inside building canopies, it is necessary to modify the existed flow patterns created by turbulence and buoyancy with imposing air movement. This air movement within the canopy is different from unpredictable and stochastic circulation of wind created by the top-canopy prevailing wind. It is postulated that the required air movement is obtainable with an active control system in the form of a pedestrian ventilation system (PVS).

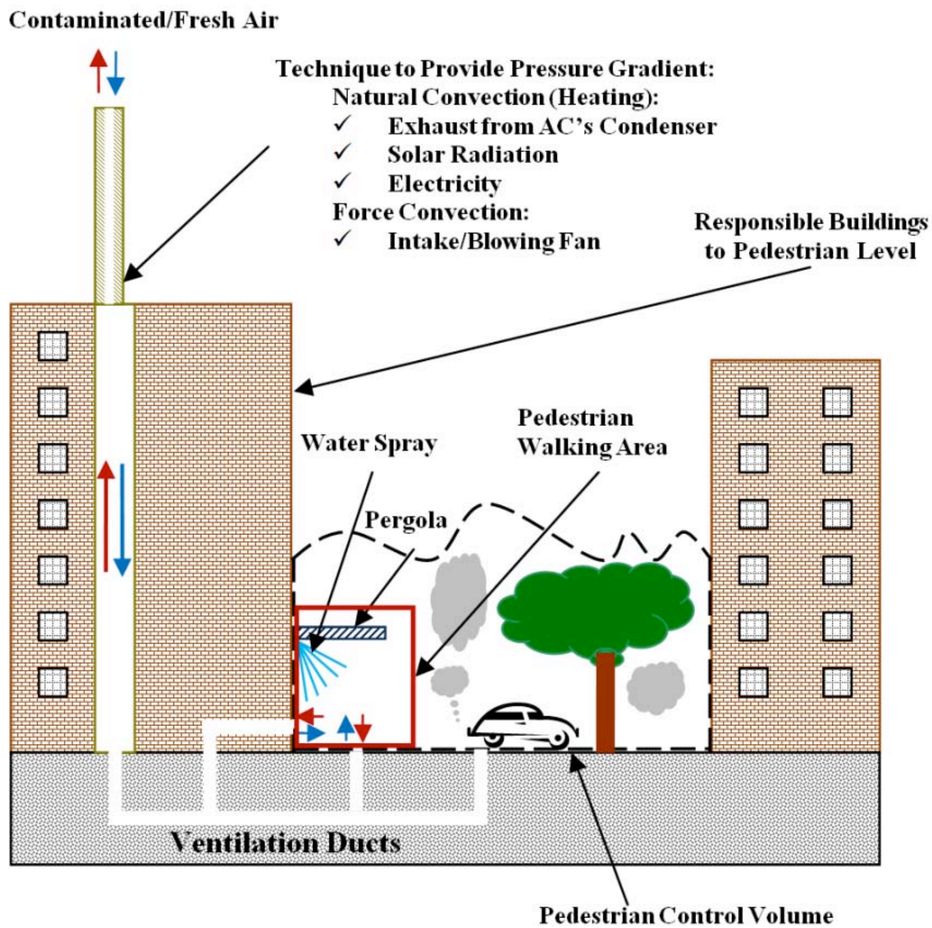
As shown in Figure 1, the PVS generates air movement in a region near the ground, the Pedestrian Ventilation Zone (PVZ), using ventilation ducts. The PVZ volume is extended around the building up to three meters in height and two meters in width (sidewalk or region in which most pedestrian activities occur). The mechanism for ventilation is based on guiding air through a designed vertical duct system from roof of the building to the surrounding street level.

In stratified situation, the street temperature is lower than the prevailing wind temperature, and thus the pollutant is mostly accumulated in the PVZ. In this case, the PVS can replace the pedestrian level air with air from the top canopy level. On the other hand, this system is also useful for bringing cooler air from the top-canopy when the weather is under unstable condition (i.e. when the prevailing wind temperature is colder than the street level temperature). Therefore, the air movement, temperature and pollution concentration in the pedestrians' region can be controlled by changing the airflow rate within the building canopy. To provide the required pressure gradient for the system, both natural and/or force convection can be used.

Heating the duct can be used to provide the required natural convection (stack flow). The required energy for heating can be provided by heat exhausted from condenser of the air conditioning systems, and/or solar energy that is mostly available during severe heat island episodes. Alternately, forced convection can be achieved using supply or exhaust fans.

When the ambient air relative humidity is not within the thermal comfort range, the pedestrian ventilation system can humidify the PVZ with some water sprays (Figure 1). Solar radiation can also be prevented using overhang (Figure 1). In this research, however, only the capability of the PVS in term of air change in addition to providing the air movement and temperature within the building canopy has been studied.

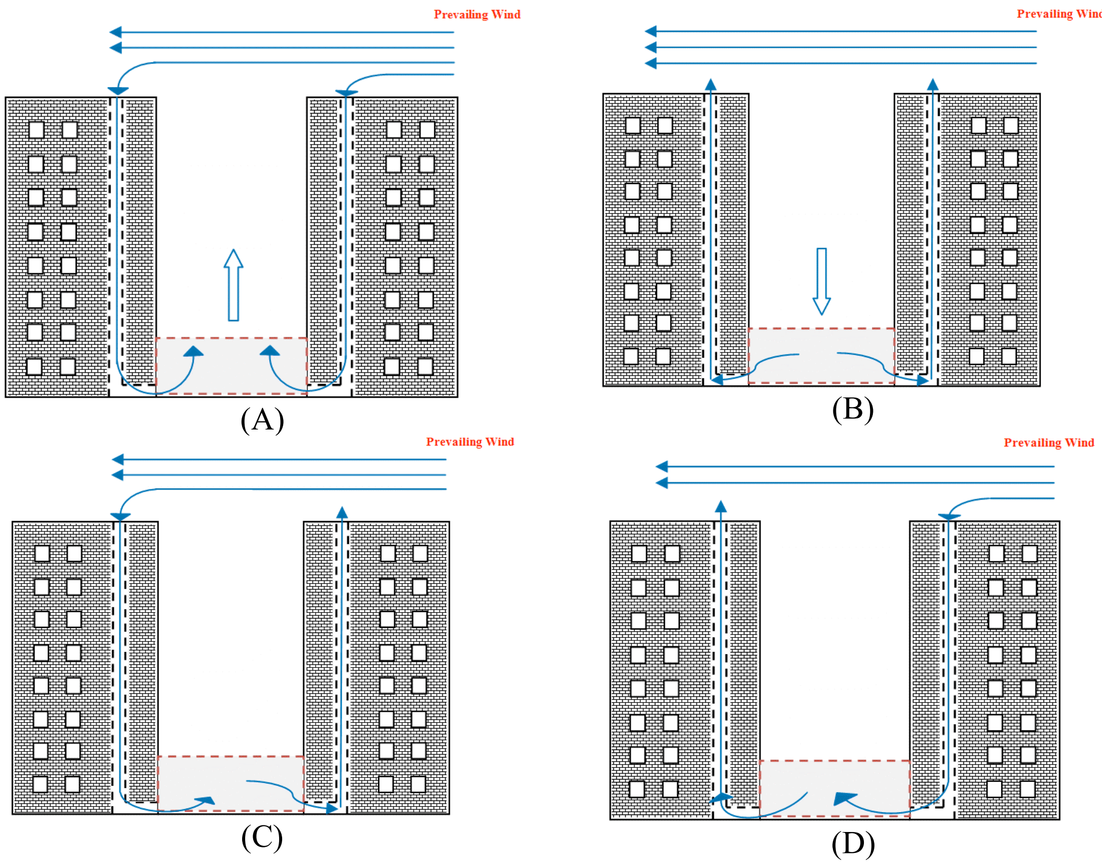
Figure 1. New Design Approach: Pedestrian Ventilation System (PVS)



Combined Pedestrian Ventilation System

It is feasible to have various way of integrating the PVS inside a canopy by installing two systems on adjacent buildings (Figure 2). In strategy (A), an upward flow toward the top-canopy can be achieved using two supply fans. Strategy (B) also uses two exhaust fans to intensify the downward flow. Strategies (C) and (D) are capable of establishing a washing flow through one building canopy to another using a supply and an exhaust fan. Obviously, the required pedestrian comfort situation is an important factor in order to choose the effective strategy. This flexibility is investigated in the following sections under both stable and unstable conditions.

Figure 2. Different Strategies of the PVS



Case study and Simulation

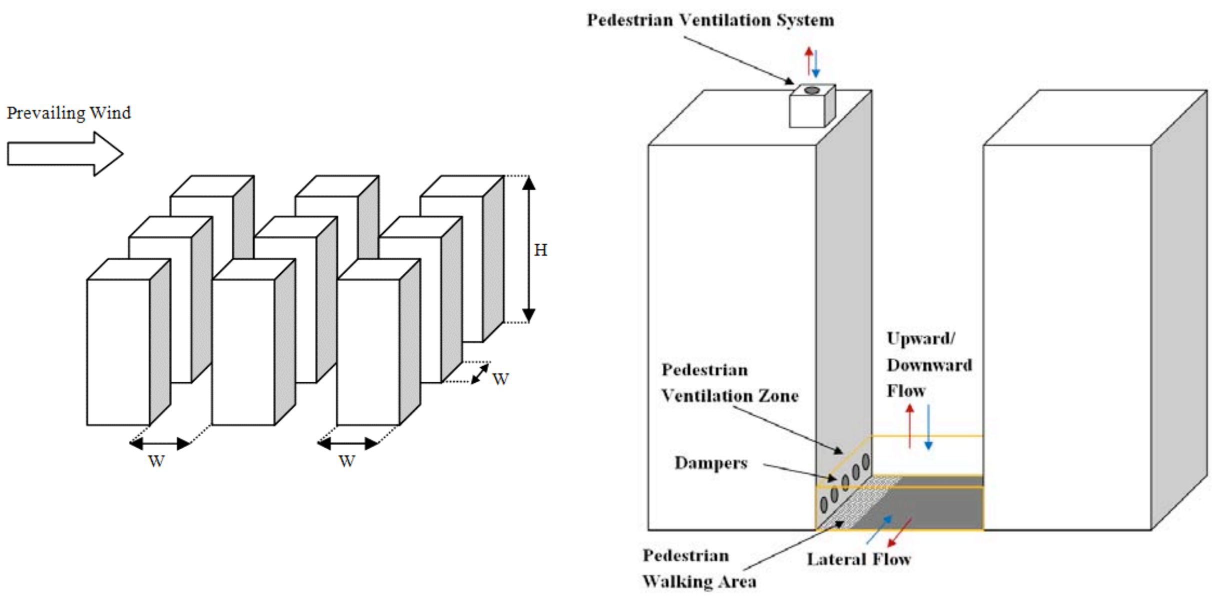
The proposed PVS in this paper is a basic concept to enhance pedestrian health and thermal comfort, during heat island and stratification period, using rejected air conditioning energy or other available forms of energy sources. Although many innovative strategies may improve the performance of the PVS, in this article only the feasibility of this system is studied. The air exchange rate (ACH) concept (Bentham and Britter, 2003) is used to quantify the pollution removal of the system.

In this paper, the air exchange rate is related to the total air that is entering or leaving from the lateral and top faces of the PVZ (Figure 3). This air movement can be later used to estimate the pollution exchange rate (PCH) of the canopy (Liu et al. 2005). It is assumed that supply and exhaust fans control airflow rate of the PVS.

A simple case study is chosen to show the capability of the PVS in urban areas. An array of buildings with simple geometry and aspect ratio of two has been selected with PVZ of 1200 cubic meter ($20m(x)\times 20m(y)\times 3m(z)$). This case study is similar to benchmark (C) of AIJ (Tominaga et al. 2008). This research only focuses on feasibility and performance of the proposed PVS.

Demonstrated in Figure 3, urban landscape has been assumed with homogenous cubic buildings with aspect ratio (the ratio of building height to its canyon length) of two. To include weather stability condition, simulation has been conducted for both stable and unstable conditions. Bulk-Richardson number has been introduced in urban canopy literature as an appropriate dimensionless number to present stability weather condition (Uehara et al. 2000).

Figure 3. (Left) Homogeneous Array of Buildings - (Right) Pedestrian Ventilation System and Zone



Shown in Table 1, two Bulk-Richardson numbers of 1.52 and -1.24 have been chosen which represent stable and unstable weather conditions, respectively (Uehara et al., 2000). The main concern in case (I), stable condition, is to remove trapped pollutant from PVZ which mostly occurs in nocturnal non-cloudy calm weather. On the other hand, case (II) is related to unstable situation in which the goal is to take the advantage of colder mean flow over the canopy.

Table 1. Proposed Case Studies

	Stability Condition	Bulk-Richardson Number	T_a = Wind Temperature (°K)	T_f = Ground Temperature (°K)
Case I	Stable	1.52	78	21
Case II	Unstable	-1.24	20	79

Four different approaches of the integration of PVS presented in Figure 2 are simulated for cases I and II. Numbers of assumptions are made in the simulation: 1) the cross-section of the ducts is circular shapes, 2) five dampers are placed on each face of the building canopy with an area of one meter square (Figure 3), 3) the duct surface is assumed to be well insulated (ignoring heat conduction losses/gains), 4) to provide the required airflow rate, adequate supply and/or exhaust fans with pressure differences of 100 (pa) are also assumed, and finally 5) radiation modeling and humidity calculation are neglected in this study to simplify the calculation.

Solution Scheme

The PVS has been simulated with Computational Fluid Dynamics (CFD) approach using FLUENT software (Fluent 2008). Around a half-million structured meshes have been generated using a commercial package, GAMBIT (GAMBIT 2008). Also, half of the domain has been computed due to symmetry of the cases. Steady scheme has been used with standard $k-å$ model for turbulent closure. Tominaga et al. (2005) used different turbulence models and concluded that the standard $k-\varepsilon$ model provides almost the same result as the other models except for the circulating flow region behind the building. Initial condition for the PVS is set as tested by Uehara et al. (2000). The boundary conditions and solution schemes are also explained in Table 2.

Table 2. Boundary Conditions and Solution Schemes

Inflow boundary	Logarithmic flow Tominaga et al. (2005)
Outflow boundary	Zero gradient assumption
Ground boundary	Logarithmic law with roughness length (0.024m)
Upper and side surface of domain	Free slip wall condition
Building surface boundary	Logarithmic law for smooth wall
Turbulent scheme	Standard $k-\varepsilon$
Advection scheme	Second order Upwind for velocity and pressure
Computational domain	$180m(x)\times 280m(y)\times 120m(z)$

Results and Discussion

The result for various strategies s of the PVS integration is illustrated in Table 3. Presented airflow rate in this table is attributed to air leaving (positive number) or entering (negative number) top pedestrian zone and two lateral faces. Also, mean temperature and velocity are measured at 2m above the ground and through the sidewalks.

Table 3 shows that in both stable and unstable weather condition, where the PVS is not working, a weak circulation flow exists inside the building canopy. This circulation generates a slight stack flow that takes the air from lateral surfaces to top-canopy surface. However, that polluted and warm air is mostly exchanged between adjacent buildings canopies without considerable vertical mixing.

In stable condition (Rb=1.52), strategy (A) supplies top-canopy air to the building canopy and produces strong air movement within the building canopy. This air is warmer than canopy air in stable condition. However, colder air temperature and higher air velocity can be obtained by using other strategies.

In the case of using strategy (B), the PVS is apparently capable of exhausting air from the PVZ. Where this strategy, using exhaust fans, is considered, the PVS removes whole the PVZ volume (1200 cubic meter) around once per 80 seconds. It means that this strategy is useful where the pollution concentration is high inside the building canopy. The lateral and top-pedestrian air flows are entering the PVZ and leaving through the PVS.

Table 3. Results for Different PVS Strategies under Stable and Unstable Conditions

Strategy	Without PVS	A	B	C	D
Stable Condition (Bulk-Richardson = 1.52)					
Airflow rate to the PVZ from lateral surface (m^3/s)	-2.82	-6.60	2.50	-3.00	0.03
Airflow rate to the PVZ from top-pedestrian surface (m^3/s)	2.82	-6.74	13.25	3.96	2.41
Mean temperature of sidewalk ($\circ K$)	334.3	335.0	335.3	334.4	334.4
Mean velocity of pedestrian sidewalk (m/s)	0.2	0.9	0.4	0.7	0.6
Unstable Condition (Bulk-Richardson = -1.24)					
Airflow rate to the PVZ from lateral surface (m^3/s)	-3.71	-6.87	0.48	-4.92	-1.54
Airflow rate to the PVZ from top-pedestrian surface (m^3/s)	3.71	-6.66	14.50	4.91	3.54
Mean temperature of sidewalk ($\circ K$)	313.7	311.0	310.1	311.1	309.5
Mean velocity of pedestrian sidewalk (m/s)	0.2	0.7	0.4	0.7	0.6

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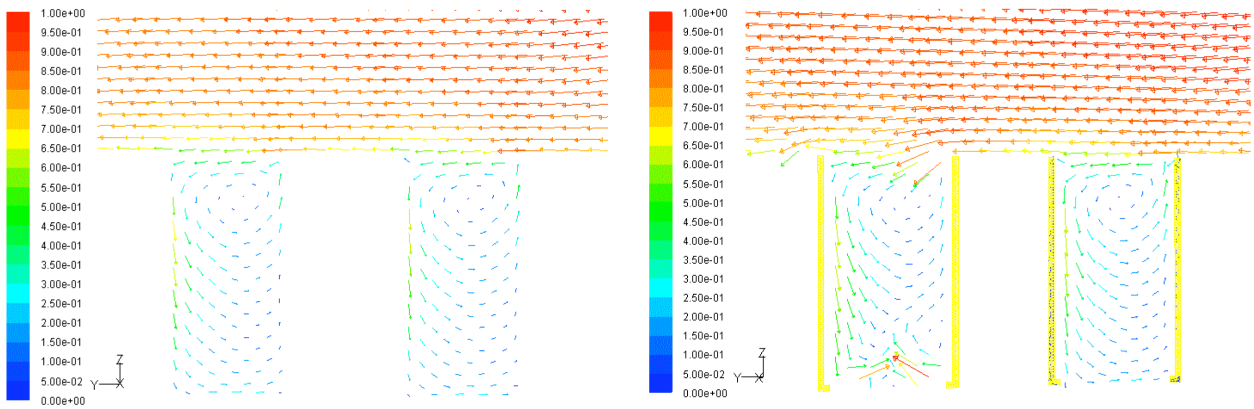
Also, from Table 3, it is clear that temperature in all strategies does not significantly change. However, strategies (C) and (D) provide appropriate air velocity within the pedestrian sidewalks. Generally, strategy (A), supplying mechanism, prepare better air velocity, temperature and exchange for pedestrians. Each 80 seconds the pedestrian ventilation volume can be removed once. The temperature remains almost the same and wind velocity increases from 0.2 m/s, light air situation (Lawson and Penwarden, 1975), to 0.9 m/s or light breeze range. Figure 4 shows velocity vector distribution before (left figure) and after running (right figure) strategy (B) of the PVS.

Under unstable weather situation (Rb = -1.24), and before running the PVS, there is a weak air circulation, however, stronger than stable condition inside the building canopy. Also, a similar air mixing with stable condition exists between lateral faces of the adjacent building canopies.

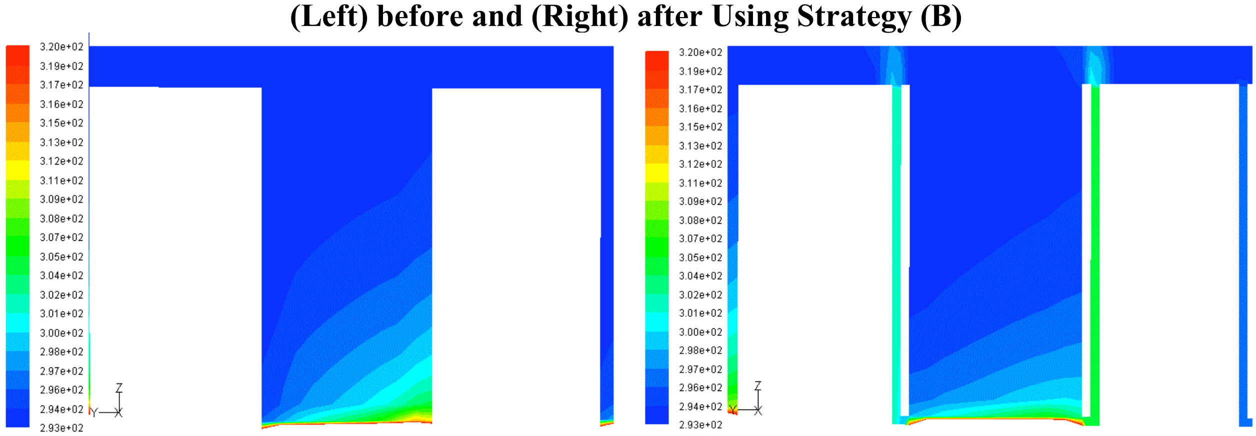
Figure 4. Velocity Vectors (m/s) inside Building Canopy
(Left) before and (Right) after Using Strategy (B)



After running the PVS, as shown in Table 3, the flow considerably alters similar to the stable case. However, the prevailing wind is colder than building canopy air in unstable condition, and strategies (A) and (B) are appropriate to guide this colder air through the building canopy. Sometimes part of the supplied air in strategy (A) might come back to the canopy. Therefore, it is more reliable to remove ambient air through the ducts using strategy (B). However, strong air exchange rate in addition to proper air velocity and temperature within the pedestrian sidewalks can be obtained using strategy (A). Temperature distribution before (left figure) and after (right figure) running strategy (B) of the PVS is presented in Figure 5.

Also, wind velocity demonstrates same range in all cases. Illustrated in Table 3, strategies (C) and (D) are appropriate options where there are many vehicles and pedestrians, and washing flow from one sidewalk to another one is desired. It can be seen that temperature reaches its minimum value in strategy (D).

Figure 5. Temperature Distribution (°K) inside Building Canopy
(Left) before and (Right) after Using Strategy (B)



Although two cases under stable and unstable weather situation have been investigated, presented opportunities are not unique solutions of this system. As mentioned previously, other parameters may suggest using strategies which are not appropriate in studied cases. For example, flow circulation regime majorly changes in higher building aspect ratios. Therefore, better strategy may come out completely inverse from presented solution in this paper. Future works will focus on parametric study of the pedestrian ventilation system.

Conclusions

A novel street canyon ventilation system, pedestrian ventilation system, has been introduced to improve pedestrian level air quality, especially within high-rise building areas. An active control technique is used in this system to enhance human comfort parameters including, the air exchange, temperature and velocity inside the pedestrian sidewalks.

To show the applicability of the proposed strategies two case studies have been carried out using CFD simulation. The results fairly show the ability of this system to provide air movement inside the building canopy under stable and unstable weather condition considering the air exchange rate criteria. Moreover, simulation results demonstrate that the PVS can bring top-canopy air to the PVZ when weather is under unstable condition.

To propose the PVS as a practical ventilation system, more experimental and simulation based on influential parameters are needed. Also, to achieve more realistic results, coupling of heat storage, humidity and radiation models with CFD simulation is strongly recommended.

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