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Plant-based Green Wall in Office Environment-Part 2: Steady-State Numerical Simulations

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ABSTRACT

Plant-based vegetation systems are economically feasible and energy-efficient applications to reduce particle matters and volatile organic compounds in indoor environments. The impact of these systems depends on their location and operating conditions. This study focuses on the impact of a real plant-based green wall system, which consists of 128 plants, on a real L-shaped office environment with a total area of 162 m^2. The steady-state numerical model is constituted for the whole office area and the trends of air velocity and the air exchange per hour are investigated in the office. The results are compared to the same office environment without green wall scenario, and it is seen that the air exchange per hour is improved by more than 40% for the whole office environment at 1 meter level above the office ground. The outputs of the steady-state model are also found useful for further simulation cases including a transient investigation

Keywords: green wall, vegetation systems, indoor greenery, indoor environment, air quality, computational fluid dynamics.

1. INTRODUCTION

The role of indoor air quality (IAQ) has been increasing in our life over time as we spend 80% of our time for daily activities in indoor areas like offices, homes, recreation rooms, etc. [1]. Therefore, the IAQ has a great impact on our health, even more important than outdoor air quality [2-4]. In case of low IAQ, health concerns related to chemical sensitivity and sick building syndrome can be observed. [5]. In general, mechanical ventilation and filtration solutions [6-8] are well-known ways to maintain a good IAQ; however, they also play a vital role in energy consumption from the viewpoint of the building energy efficiency concept. As an alternative to the mechanical solutions, a plant-based green wall is a biological-based IAQ solution that is based on real and live plants placed onto a vertical wall body to reduce the particulate matters (PM) and volatile organic compounds (VOCs) using them as the energy source of the live plants [9]. Compared to other biological-based solutions that use microorganisms, biofilms, etc. instead of real plants, the plant-based green walls have lower maintenance costs, lower energy consumption, and a better aesthetic view [10]. On the other hand, similar to mechanical solutions, the selection of convenient plant-based green wall solutions depends on the operating environment. The size of the indoor environment, location of the green wall, the impact of green wall operation on the velocity contours (to avoid discomfort for occupants), and its positive impacts on the air exchange per hour (ACH). The mentioned parameters make each green wall application is unique and specific for the target indoor area. To this point, the current study aims to perform steady-state numerical simulations for a real green wall structure in a real office environment in Singapore. The current study is a steady-state effort that aims to provide brief information about velocity and ACH trends in the large office environment. However, the fact is the office environment is a real place and affected by dynamic changes with multiple numbers of parameters like varying number of occupants, pantry activities in the office, varying periods of using the computational

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devices, meetings, etc. All these issues can be considered in a complex and more detailed transient model, which must be validated with a complicated experimental measurement in the same environment, but it is out of the current scope of the work as our main goal is understanding the basic velocity and ACH contours.

2. COMPUTATIONAL MODEL

The computational model is developed in two different parts: 1) the whole office space and 2) the green wall. The computational domain of the whole L-shaped office environment with a total area of 160 m^2 and a height of 3 m is shown in Fig. 1. Only open areas are considered in the simulation while the closed environments are considered shut. Two access doors (red-colored in Fig. 1) are also considered shut. The office temperature is constant at 23°C thanks to the adjusted energy balance between the heat sources (people, electronic equipment, etc.) and heat sinks (air conditioning system components, passive displacement units, etc.). The fresh air is supplied from the main duct (shown in Fig. 1) with the supplied air temperature of 16°C, airflow rate of 236 l/s, and flow velocity of 1.7-1.9 m/s. Fig. 1 also shows the computer-aided design model and real image of the green wall which is located in the corner of the office (blue-colored part). The wall consists of 64 plants on each side; namely, 128 plants (in the plant holders) are vertically held on the plant containers in the green wall (Fig. 1) structure with the dimensions of 2×0.35×1.2m. A single type of plant is used in simulations. The active area of the green wall is 70% with a total fan capacity of 800 m^3/h. That is, one face of the wall has four fans placed in fan housings (Fig. 1). The fans suck the ambient air to push it down through the plants. Hereby, the sucked air is purified while they are passing through the plants and the released air from the wall is called treated air. In the whole office domain, the supplied fresh air is the velocity inlet while the pressure outlet is fans. As the windows and walls are airtight in the real case, the external walls and windows are assumed airtight as well.

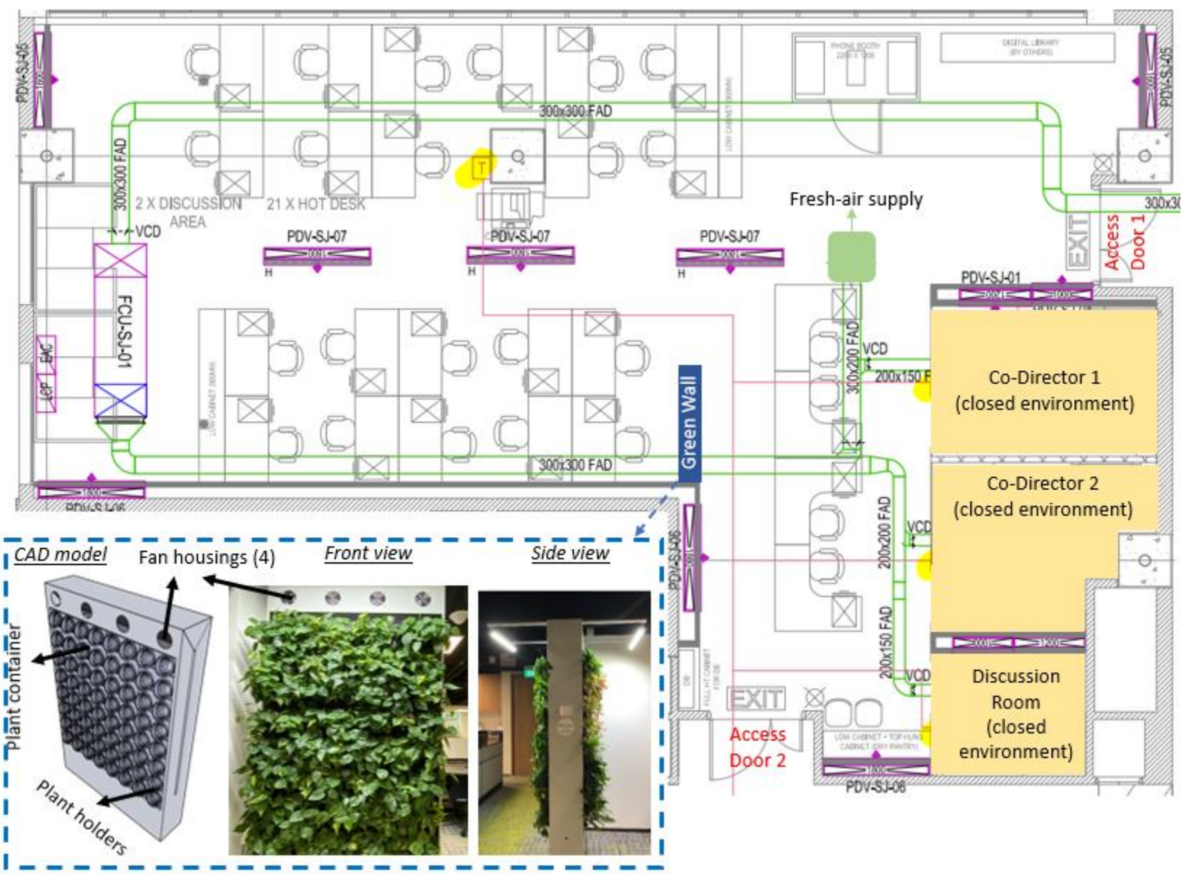

Fig. 1. The office layout and the green wall structure.

Besides the whole domain, we also look at the green wall domain in detail. Fig. 2 shows the computational model of the green wall in the simulation environment. Even though the existing design has 64 plants on each side (in total 128), the computational model is built by considering symmetries in the model. That is, we consider a single side of the wall at first; then, selected the central four plant holders. Hereby, the symmetry considerations decreased the computational cost and time whereas it provides advantages in mesh refinement. Since we want to see the flow-related contours near the wall body, we also build an air volume that is adjacent to the wall as shown with red-lined rectangular parallelepiped in Fig. 2a. The mesh type is cartesian for the office environment with a mesh size of 1.5 million mesh cells. The meshing structure is presented in Fig. 2b.

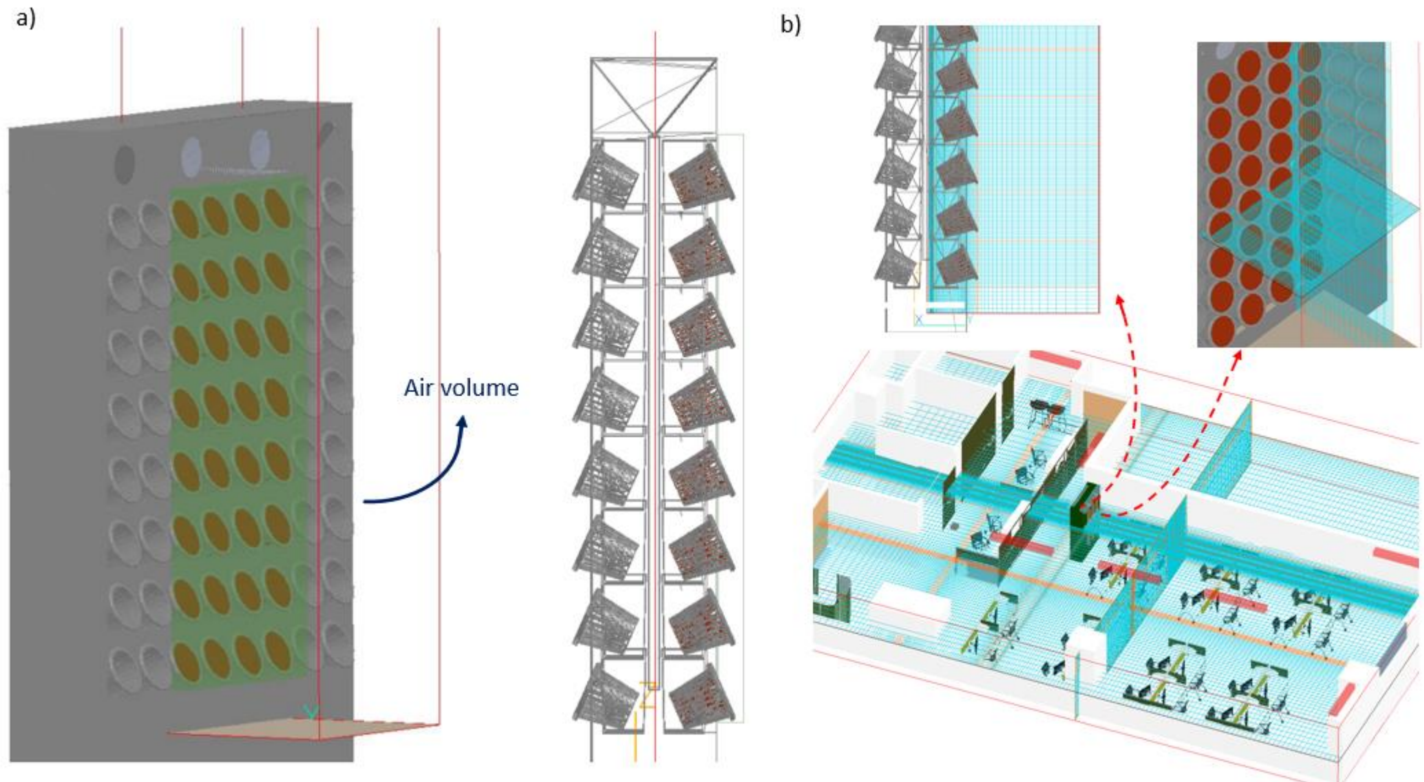

Fig. 2. The numerical model of the green wall and office environment; a) computational model and b) mesh structure.

The flow rate of the green wall (via fans) is 400 m^3/h (at each face); we use the flow rate of 100 m^3/h since we modeled the quarter of the whole model following the symmetrical conditions of the wall. The face of the computational volume looking at the green wall surface is set to a pressure boundary with an exterior pressure of 0 Pa. This is an engineering assumption of this study. Due to the soil and root structure of the plants, the airflow through the plants can be considered as the flow in a porous medium. The flow in the porous medium can be defined with Darcy's law as shown in Eq. 1,

$$Q = \frac{K \cdot A}{\mu \cdot L} \Delta P \tag{1}$$

where Q is flow rate, K is the permeability of the soil, A is the flow area, μ is viscosity (air), L is the thickness of the porous medium, and ΔP is the pressure drop. The current porous medium in the plant holders has five main components; i) silt, ii) plant roots; iii) filter bag, iv) gravels, and v) clay. There is no fully accurate way to predict or calculate the permeability value of the porous medium due to the complex and natural structure of the plant box. However, considering the permeability values of these components and mostly focusing on the silt since the vast majority of the plant box is occupied by silt [11, 12], the permeability value is assumed 1×10^{-7} m/s in this study. To this end, the pressure drop is calculated at nearly 6.2 Pa for each plant box. Note that this value changes when the permeability value increases or decreases. The computational model is solved by using the commercial code of PHOENICS, which belongs to CHAM Limited, UK (please see Acknowledgment). Since the office temperature is assumed well-maintained at 23°C, the computational study only focuses on the numerical solutions of the mass and momentum equations, as shown Eqs. 2 and 3, respectively,

$$\nabla \cdot \vec{\boldsymbol{v}} = 0 \tag{2}$$

$$\rho \left(\frac{\partial \vec{v}}{\partial t} + \vec{\boldsymbol{v}} \cdot \nabla \vec{\boldsymbol{v}} \right) = -\nabla p + \mu \nabla^2 \vec{\boldsymbol{v}} \tag{3}$$

where $\vec{\boldsymbol{v}}$ is the velocity vector of air, t is flow time, ρ is the density of air, p is the pressure, μ is the dynamic viscosity of water. The modified version of the k-epsilon turbulence model by Chen and Kim [13], is used for solving the governing equations since the original k-epsilon model may not present consistent solutions for recirculating and swirling flows [14] that are valid in the current green wall domain. The full convergence was achieved during the simulations with less than 0.1% errors for all parameters.

3. RESULTS AND DISCUSSION

Computational simulations focus on airflow behaviors in the office environment The airflow behaviors are analyzed according to i) velocity contours and ii) air exchange per hour (ACH), which are both important signs for IAQ and thermal comfort [15]. Fig. 3a illustrates the velocity contour through a horizontal section in the office layout. The velocity values are seen in the range of 0.01-0.3 m/s in the office except for near air volumes of the green wall. Near the green wall, the velocity can reach up to 0.5 m/s due to the gaps between the plant holders of the green wall. These gaps are design-related issues so that the velocity values can be easily reduced and maintained well with better design solutions. Even though these gaps increase the velocity near the green wall, they do not affect the occupants since their impacts are local and do not affect other regions. Fig. 3b shows the velocity contours through a vertical section with reference to the middle section of the green wall.

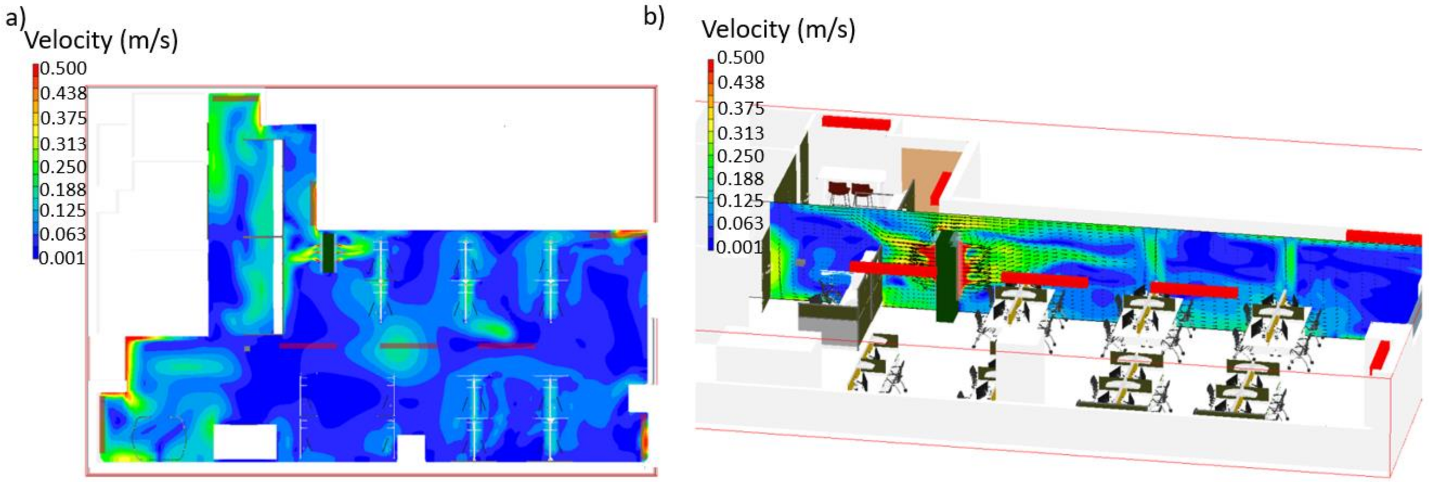

Fig. 3. Velocity contours in the office environment with the green wall; a) horizontal (1m above the floor) and b) vertical section.

It is seen that the velocity increment due to the gaps between plant holders create a high-velocity region but it does not affect the occupants in the room, even the occupant who sits closest to the green wall. However, as mentioned above, the design improvement can improve the velocity field near the green wall. Furthermore, a modified design (reducing the gaps between plant holders) will be able to provide better conditions for air purification via plants. Following the velocity-related simulations, we can state that the air ingestion through the fans or air blowing from the green wall to the indoor environment does not affect the air velocity field in the office space. On the other hand, Fig. 3b shows that the desk located in front of the green wall blocks the effective distribution of the purified air in the room. Although validating the steady-state results with real dynamic conditions cannot present fully accurate outcomes, we compare the simulation data with the real measurement in the office according to a single location where is just near the fresh air supply point. The velocity value measured ranges between (nearly) 0.420-0.470 m/s in real case whereas the steady-state numerical simulation shows the velocity value of 0.462 m/s. This shows that the steady-state model is in good agreement with a specific moment of the dynamic measurement. It is worth noting that this is a partial validation; full validation should be conducted with transient simulations. Besides the velocity contours, air change per hour (ACH) is another critical consideration for flow simulations and it is presented in Fig. 4a. The ACH contours infer that the green wall provides higher ACH values around its near environment. Also, the locations of the access doors increase the ACH values. Thus, the left side of the office (contours with different shades of blue) has higher ACH values than the right-side of the office (contours with different shades of green color). Since a higher ACH value may lead to better indoor air quality, another green wall implementation can be suggested for the right-side of the office. In addition, the ACH simulations also show that the location of the desk in front of the green wall negatively affects the ACH contours. That is, if the distance between the desk and green wall is increased or the desk is relocated to another place in the office, ACH (and fresh air distribution) can be more effective that is consistent with the results of velocity contours in Figure 3. To better understand the positive impact of the green wall on the ACH, the simulation of the office environment without green wall implementation is presented in Figure 4b.

As shown in Figure 4b, the left-side of the office space (different shapes of green color) has greater ACH values than the right side of the office space (different shapes of yellow-color). It is mostly thanks to the locations of the access doors that increase the ACH. However, compared to the green wall case in Figure 4a, the green wall increases the ACH values nearly by 48.5% and 38.5% (according to colors of ACH trends) at the left- and right-side of the office space, respectively. Moreover, when we look at the region where the green wall is located, it is seen that the green wall increases the ACH nearly by 95%. To this end, it can be stated that the green wall implementation provides remarkable positive impacts on the indoor air quality thanks to fresh air distribution and higher ACH values whilst the occurred velocity fields do not significantly affect the occupants. It must be noted that the given increment rates above are based on steady-state numerical analyses solving only the momentum and mass equations as explained in the computational model. Since the real environment is not a steady environment, and it is affected by dynamic changes like changes in the number of occupants, impacts of thermal load (from occupants and computation devices), etc., the improvements of ACH in a real environment would be different than the current steady-state model. Therefore, we can state that the current steady-state model gives us a useful insight but not exactly correct improvement trends. To investigate the closest scenario to a real environment, the computational model should be transient and include an energy equation after being validated by an experimental study that is based on a huge number of thermal/flow sensors in the large office environment. Also, relocating the desk in front of the green wall can increase the fresh air distribution and ACH trends at the same boundary conditions.

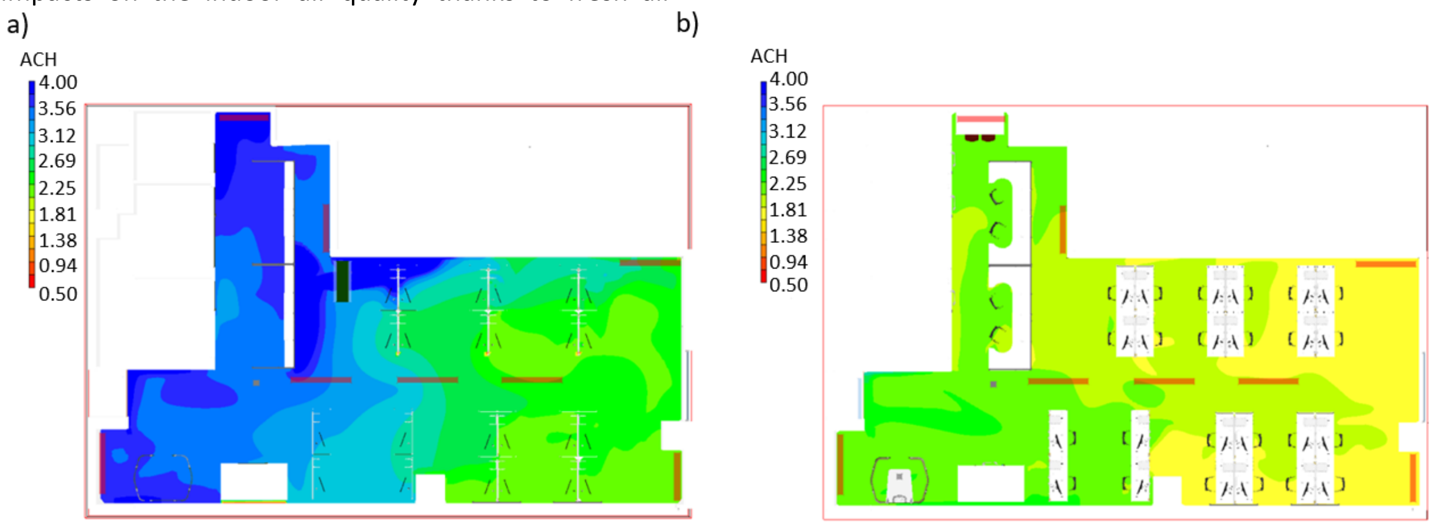

Fig. 4. ACH contours in the office environment with the green wall (1m above the floor); a) with green wall and b) no green wall.

There are also some limitations and uncertainties. The simulations are applied under steady-state conditions, which are different from real conditions as the real environment is fully dynamic and transient. Due to the large area of the office environment, experimental verification is also very challenging so that verifying the current steady model via experiments has too many limitations and therefore uncertainties. Since we focus on the velocity contours and ACH trends, the steady-state simulations provide sufficient information to us on the current purpose but further and more detailed simulations (e.g. transient simulations, experimental verifications in a lab-scale environment, etc.) are required for investigating the real case-like computational environment, particularly for simulation domains that take the energy equation into the account.

4. CONCLUSIONS

The presented study performed steady-state numerical simulations for a real green wall structure in a large and L-shaped office environment with the total area of 160 m^2. The impact of the green wall on the velocity and air exchange per hour was analyzed via computational fluid dynamics. The results deduced that there was a small high-velocity air volume very near the green wall due to the small gaps between the plant holders of the green wall, but the velocity fields did not affect any occupants, even the closest one to the green wall. However, it was seen that there should be a distance between the office desks and the green wall to provide a more effective treated air distribution to the entire environment. The air exchange rate simulations showed that the green wall increased the ACH nearly by i) 95% its around, ii) 48.5% at the left-side of the office (where the access doors exist), and iii) 38.5% at the right-side of the office according to the obtained velocity and ACH contours. At the end, it was seen that the green wall implementation increased the air exchange per hour significantly; and therefore the air quality. However, the location of the green wall and the shape of indoor environment were two main parameters that strongly affected the velocity and ACH trends. Regarding the numerical findings, future studies can focus on the simulations of single green wall at various locations or multiple green wall structures in the same area. Hereby, the impacts of the locations and the number of green walls can be analyzed from the viewpoints of velocity and ACH. Also, numerical efforts can focus on the interior design of the green wall, especially for the newly designed green wall versions. Hereby, a better analysis of pressure drops, and velocity gradients can be done. Furthermore, the computational model can be improved via more complex and energy equation-integrated solution algorithms to better mimic the real environment whilst the model calibration and verification can be obtained via multiple numbers of thermal/flow sensor measurements. The findings can also be useful for determining the economic performance and feasibility of the green wall solutions in building energy efficiency-related applications.

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