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Numerical Simulation of the Microclimate in the Vicinity of Green Boundary Walls

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ABSTRACT

Boundary walls, which are important for security, privacy, and partition of lands, can act as a heat source, creating a less comfortable microclimate. Green walls, where vertical surfaces are planted with greenery, have been proposed as a potential solution to improve thermal comfort in the urban environment. Studies investigating how the variation of species, and planting patterns can create the optimum microclimate, would be beneficial in this regard. Numerical simulations can play a major role for such studies where the effects of variation of species and planting patterns can be efficiently studied without using experimental set ups which are resource-consuming. This research attempted to develop such numerical simulation for boundary wall greening options and attempted to validate the results for the two microclimatic parameters, namely temperature and relative humidity (RH). Two boundary walls used in a previous experimental study were numerically modeled and validation was done using the previous data, a green boundary wall option and a bare wall option. The numerical model predicted a maximum difference of 2.2ºC in temperature and a 5.1% difference of relative humidity increase near the green wall compared to the control wall. The model developed for the temperature showed substantial success while the RH model required further refinement. Future research work can attempt to improve model accuracy through the introduction of temporal variation of wind speed and transpiration rates.

KEYWORDS: *Boundry wall, Computational Fluid Dynamics, Green wall, Microclimate, Numerical Modelling*

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1 INTRODUCTION

1.1 Background

With the global temperature increase and the urbanization rate increase, creating a comfortable macro climate for urbanized areas is becoming an important issue. In recent years, boundary walls became more and more important in urban areas for security, privacy, and partition of lands. Nevertheless, boundary walls made with cement blocks, especially bare walls, have also become a key reason for the urban heat island effect (Akbari et al 1998) negatively affecting the process of maintaining a comfortable microclimate in urban areas. As a solution, green walls, created by the greening of vertical surfaces with selected plant species (Manso & Castro-Gomes 2015) are introduced.

Many previous research work (Galagoda et al 2018, Jayasundara et al 2017, Rathnayaka et al 2015) experimentally investigated the effective performance of installing green walls in urban areas. Experimental investigations would aid the researcher in studying the performance of limited greening options through experimental data. However, experimental research limits the range of options to be investigated. To overcome this challenge, several research works (Djedjig et al. 2015, Scarpa et al 2014) have experimented with numerical/mathematical modeling of green walls enabling researchers to study the performance of a range of greening options without actually having to construct and experiment on them. As a result, the effectiveness of a range of green wall design options through the variation of species or wall configuration can be studied. Thus, numerical simulation of green walls bridges a very important research gap. By applying the vertical greenery concepts to boundary walls, several experimental studies (Jayasundara et al 2017, Rathnayaka et al 2015) have investigated about the effectiveness of green boundary walls. However, research work investigating numerical simulating the green boundary walls have not been conducted to the best of the authors' knowledge. If such numerical studies exist, the performance of different greening options can be studied without actual construction. While researchers numerically simulating the green walls in buildings have found the possibility of effectively simulating those, it is not known whether numerical simulations can successfully predict theperformance of green boundary walls. This research aims to address the research question of investigating whether numerical simulations can successfully predict the performance of green boundary walls.

1.2 Literature Review

1.2.1 Introduction of greenery to create a comfortable urban space

When a city or an area experiences a higher temperature than the outlying areas it is known as an Urban Heat Island (UHI). This is a result of the increase of heat generated by urban structures as they consume and re-radiate the solar radiation and heat from anthropogenic heat sources such as vehicles, air conditioners, and power plants (Rizwan et al. 2008). One of the most effective ways to mitigate the effect of UHI is to develop a network of urban green spaces (Szkordilisz, F 2014). Studies show that green wall systems can improve thermal comfort indoors by controlling heat gains and losses (Manso and Castro-Gomes 2015). Further, the use of greenery contributes to mitigate air pollution (Wolverton et al 2021), noise absorption and sound attenuation (Renterghem et al 2013) while reducing the Carbon footprint and increasing aesthetical appearance. Additionally, as per Madushanka et al, (2022) relaxation effects, enhanced aesthetic appearance, increased proximity to nature, and improved air quality are highly appreciated benefits of urban green walls. Since green walls and green roofs can be incorporated into the existing buildings and would not take up any extra space from the urban area, it is one of the best ways to increase greenery in a given urban area.

1.2.2 Numerical simulation of green walls

The authors were unable to find literature directly focusing on numerical modeling of temperature and humidity in the vicinity of green boundary walls. Thus, research related to green walls in the buildings was reviewed. The effectiveness of living walls for their thermal behavior was studied through a mathematical model (Scarpa et al, 2014). In this study, modeling was conducted using equations for the mass and heat balances as well as a general equation for the evapotranspiration of a reference plant. The evapotranspiration phenomena were incorporated in the mathematical model using both a calculating system and a general thermal model. The developed mathematical model was able to forecast the thermal behavior of living walls and the results were validated against experimental data. Djedjig et al (2015) proposed a model for green roofs and green walls using

TRNSYS. Experimental readings were used to confirm that the model was successful. Widiastuti et al (2021) discussed the effect of vegetated walls on indoor thermal performance by using a Computational Fluid Dynamic (CFD) simulation. According to the study, the bare wall model temperature ranged between 28.0ºC - 32.2 ºC while the vegetated wall building showed a range between 28.0 ºC to 28.5 ºC. In field measurements of the vegetated wall model, the temperature ranged between 23.0 ºC to 24.7 ºC while the indoor temperature of the bare wall model was distributed between 26.5 ºC to 30.2 ºC. A study by Hosseinzadeh et al (2022) investigated the effect of green roofs, green walls, and trees on air quality. These numerical simulation studies revealed that vegetated walls reduce the temperature by a substantial value.

1.2.3 Research work on the effectiveness of green boundary walls

According to the experimental work of Jayasundara et al. (2017), introduction of greenery to boundary walls has led to a decrease of temperature (a maximum of 4.2ºC) in comparison to the bare cement block boundary wall. The bare wall showed 5% less of relative humidity compared to the green wall. Another experimental study done in Sri Lanka shows that the non-vegetated boundary wall is about 1.2ºC higher than the atmospheric temperature, while the vegetated panels are about 0.8ºC lower than the atmospheric temperature (Rathnayaka et al 2015). According to Halwatura & Nishad (2012) readings taken in a low greenery environment and a green environment in Colombo, Kandy and Nuwaraeliya (Sri Lanka) had a temperature difference around 2ºC. An analysis of the temperature differentials at a distance of 0.1 meters from the green wall surfaces T1, T2, and T3 (T1-living walls, T2- indirect green façades and T3- direct green façades) compared to the bare wall controls revealed maximum temperature differentials of 0.71°C at 1:00 PM, 0.94°C at 12:00 PM, and 1.81°C at 1:00 PM, respectively according to Galagoda et al (2018).

The majority of the studies regarding green walls have been conducted as experimental studies on real or scaled-down models. Only a few research have attempted to model green walls numerically. While green walls are found to mitigate the effects of urban heat islands significantly, the identification of optimum green wall arrangements is an important research problem. Building real-life or scale-down models poses constraints such as time, space, and resources. However, numerical modeling of green walls would aid in understanding the performance of different green wall types without having to create several green walls. Such numerical modeling can be instrumental in encouraging people to construct green walls or use detached green walls.

1.3 Research Aim and Objectives

This study aimed to investigate whether the numerical simulation of boundary walls can be effective in simulating the thermal performance (i.e temperature and humidity) of boundary walls for different boundary wall greening options. Specifically, it attempted to address the below research objectives.

A. Investigate the effectiveness of numerical simulations to simulate the temperature around the green wall and bare wall.
B. Investigate the effectiveness of numerical simulations to simulate the relative humidity around the green wall and bare wall.

2 RESEARCH METHODOLOGY

The summary of the research methodology is given in Figures 1 and 2. Modeling humidity and temperature around the green wall was done in two steps using COMSOL Multiphysics 5.6.

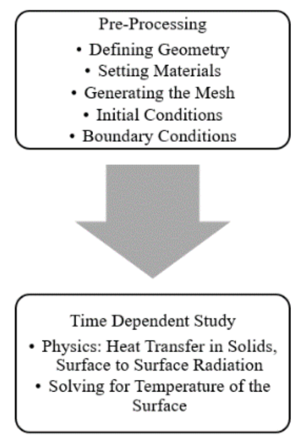

Figure 1. Modeling the temperature of the ground and the bare (cement block) wall from 10 AM to 3 PM

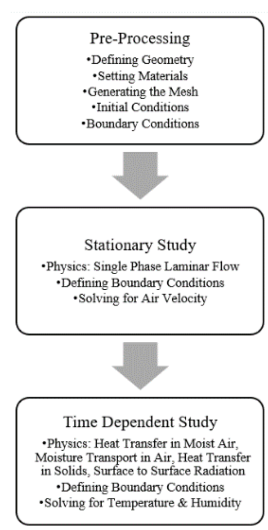

Figure 2. Modeling the temperature and humidity around the wall from 10 AM to 3 PM

In order to model the temperature on the ground and the bare (cement block) wall, the physics features of COMSOL Multiphysics 5.6, 'Heat transfer in Solids and Surface-to-Surface radiation' were used with the Multiphysics coupling 'Heat transfer with Surface-to-Surface Radiation'.

The source of heat for this model was solar irradiation, which was included using the feature 'External Radiation Source' feature. In this feature, the longitude, latitude, time zone, year and date were specified. Sri Jayawardenepura Kotte, Colombo, Sri Lanka was taken as the geographical location to calculate the direction of the incident solar radiation over the computed time since the experimental results were based on a green wall located in Sri Lanka.

$$q = \int_0^{\infty} \in (\lambda)\sigma(T^4 - T_{amb}^4)\, d\lambda \qquad \text{--(1)}$$

Equation 1 is the basic equation in calculating the total radiative flux, where ∈ is the wavelength-dependent emissivity and σ is the Stephan-Boltzmann constant. The temperature of the surface is given by T and is exposed to ambient temperature, T_{amb}. For the short and long wavelengths separation point, the default value in COMSOL Multiphysics of 2.5µm was used. For concrete emissivity, short wave and long wave radiation of concrete was taken as 0.65 and 0.94 respectively as per Sparrow (2017).

2.1 Diurnal Temperature variation

A daily temperature cycle is characterized by the daily fluctuations of temperature, caused by the rotation of Earth and the variation of solar insolation, or the amount of sunlight that reaches a particular area. The changing insolation levels result in fluctuations in air and surface temperatures during the progression of day and night. This cycle is known as the diurnal cycle of temperature. The diurnal temperature was calculated by using the equation below,

$$T_{avg}[1 / K] + dT[1 / k]\, cos(2\pi(x - 14) / 24) \quad \text{--(2)}$$

where, T_{avg}, the average temperature of Colombo, Sri Lanka as 29ºC and the difference between the maximum and minimum temperature (diurnal temperature variation dT) of Colombo, Sri Lanka as 6ºC (Sun's Radiation Effect on Two Coolers Placed Under a Parasol, n.d.). The limits for x were set as, lower limit :0, upper limit: 24*3600.

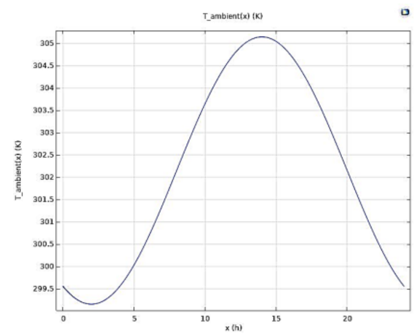

Figure 3. Diurnal Variation of the Temperature in Colombo, Sri Lanka

2.2 Governing Equations for Heat Transfer in Solids and Surface to Surface Emissivity

To model the temperature of the ground and the bare (cement block) wall from 10AM to 3PM, 'Heat Transfer in Solids' and 'Surface-to-Surface Emissivity' physics in COMSOL Multiphysics were used.

The governing equations for 'Heat Transfer in Solids' are given below.

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T + \nabla.(q) = Q + Q_{ted} \quad \text{--(3)}$$

$$q = -k\nabla T \quad \text{--(4)}$$

The governing equations for 'Surface-to-Surface Radiation' is given below.

$$J_i = \varepsilon_i e_b(T) FEP_i(T) + \rho_{d,j} G_i \quad \text{--(5)}$$

$$G_i = G_{m,j} + G_{amb,j} + G_{ext,j} \quad \text{--(6)}$$

For 'External Natural Convection', the governing equations are given below.

$$-n.q = q_0 \quad \text{--(7)}$$

$$q_0 = h(T_{ext} - T) \quad \text{--(8)}$$

The ambient temperature (external temperature) was given as a time function where the temperature varies according to the diurnal cycle temperature. The numerical study was done in COMSOL Multiphysics 5.6, as a time dependent study from 10AM to 3PM.

2.3 Governing Equations for Non-isothermal flow Multiphysics

Reynolds Number over a flat plate calculated. The density of air and the Reynolds number over a flat plate were calculated at the minimum (299.15 K) and the maximum (305.15 K) temperature of the day using,

$$\rho = p / RT \quad \text{--(9)}$$

$$Re_D = \frac{\rho v D}{\mu} = \frac{VD}{\nu} \quad \text{--(10)}$$

Where, atmospheric pressure = 1.0132×10^5 Pa, average velocity 2 m/s and characteristic length as D=0.5m. (Width of Bare (cement block) Wall). Reynolds number at 299.15K was calculated to be 64000 and at 305.15K, 62000.

The flow is modelled as a flow over a flat plate. For a flow over flat, the transition from laminar to turbulent flow occurs for 2 x 10^5 < Re < 3 x 10^6. Therefore, the air flow over the cross-section area of the bare (cement block) wall is taken as laminar flow. Liquids are incompressible fluids. On the other hand, a gaseous fluid such as air can be either compressible or incompressible. Generally, for theoretical and experimental purposes, gasses are assumed to be incompressible when moving at low speeds.

For laminar flow,

$$\rho(\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = \nabla \cdot [-p\boldsymbol{I} + \boldsymbol{k}] + \boldsymbol{F} \quad \text{--(11)}$$

$$\rho\nabla \cdot \boldsymbol{u} = 0 \quad \text{--(12)}$$

$$\boldsymbol{k} = \mu(\nabla\boldsymbol{u} + (\nabla\boldsymbol{u})^T) \quad \text{--(13)}$$

For Heat transfer in Moist Air

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \boldsymbol{u} \cdot \nabla T + \nabla \cdot \boldsymbol{q} = Q + Q_p + Q_{vd} \quad \text{--(14)}$$

$$\boldsymbol{q} = -k\nabla T \quad \text{--(15)}$$

2.4 Governing Equations for Moisture Transport in Air

The feature 'Moisture transport in Air' was used to introduce stomatal transpiration to the model. Plants reduce the temperature of their surrounding air by transpiration cooling. The conversion of liquid water in leaves into water vapor requires latent heat. This energy is obtained from the surrounding hot air and sunlight. When water is lost through transpiration as vapor, more energy exits the system than was used to convert the water into vapor, causing the system to cool in order to maintain energy balance, as per the law of conservation of energy. Since stomatal transpiration accounts for approximately 90% of total transpiration, stomatal transpiration data of *Sansevieria trifasciata* was used. The transpiration rate and Carbon Dioxide absorption per unit leaf area were measured using the TPS 2 Portable Photosynthesis System during the period of 10:00AM to 15:00PM when there was more than 2000 lux of light available. The average transpiration throughout the day from this experiment was observed to be 0.915 mmol/m^2/s.

Average total area of *Sansevieria trifasciata* leaf was calculated assuming a plant has 6 leaves per rosette and that a 1m x 1m plank would contain about 18 rosettes. The average leaf area per leaf was calculated (Sansevieria Trifasciata - Plant Finder, n.d.). Total area of *Sansevieria trifasciata* leaves was approximated and was equated to the boundary area of the green wall that would act as a wet surface. To simulate transpiration 'Wet Surface' feature of COMSOL Multiphysics 5.6 was used.

The evaporation flux g_{evap} is defined as:

$$g_{evap} = M_v k(c_{sat} - c_v) \quad \text{--(16)}$$

$$q_{evap} = L_v g_{evap} \quad \text{--(17)}$$

Governing Equations for Moisture transport in air are given in equations 18, 19 and 20.

$$M_v \frac{\partial c_v}{\partial t} + M_v \boldsymbol{u} \cdot \nabla c_v + \nabla \cdot \boldsymbol{g}_w = G \quad \text{--(18)}$$

$$\boldsymbol{g}_w = -M_v D \nabla c_v \quad \text{--(19)}$$

$$c_v = \phi_w C_{sat} \quad \text{--(20)}$$

All the notations are listed and described within the 'notations and nomenclature' at the end of the paper.

2.5 Geometry of the simulated wall

For the numerical simulation, the model was based on Jayasundara et al. (2017) experimental setup. The model's geometry is illustrated in Figure 4 and includes the components of the ground, air, bare wall, and green wall

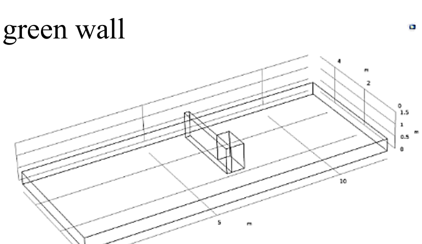

Figure 4. Geometry for Modeling the temperature of the ground and the bare (cement block) wall from 10AM to 3PM

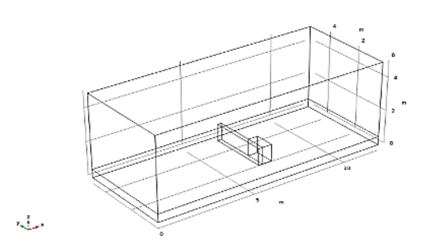

Figure 5. Geometry for Modeling the temperature and humidity around the ground and the bare (cement block) wall from 10AM to 3PM

Table 1. Geometry of the study walls

	Height (m)	Width (m)	Length (m)
Ground	0.5	12	5
Bare Wall	1	0.2	3
Green Wall	1	0.5	1

2.6 Boundary Conditions

As the temperature under the ground remains approximately constant throughout the day (Singh & Sharma, 2017), the temperature at the ground boundaries was kept at the ambient temperature (ASHRAE 2017 - Station: Sri Jayawardenepura Kotte).

The second boundary condition is the surrounding air temperature. There exists a combination of free and forced convection, due to wind, from all exposed surfaces to the ambient air, of which the temperature is assumed to vary according to the diurnal temperature cycle. A free convective heat flux on the surface was used. A heat flux was added to model the natural convection between the ground and wall surface and the external environment.

The simulation was done by using two inlets for air velocity, to gauge the most appropriate one. Since, the wind velocity was not specified in Jayasundara et al (2017), it was assumed as a normal velocity of 2m/s at the inlet.

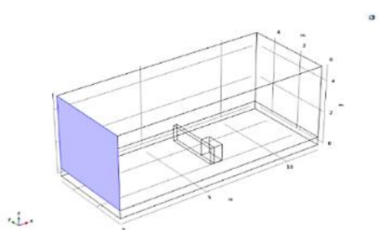

Figure 6. Inlet 1 for air flow

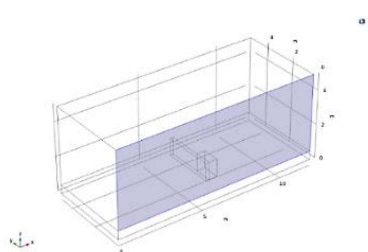

Figure 7. Inlet 2 for air flow

The wall for the laminar flow consists of the boundaries for the ground, bare (cement block) wall and the green wall. Wall condition was set to No slip condition, and translational velocity was set to zero (fixed wall).

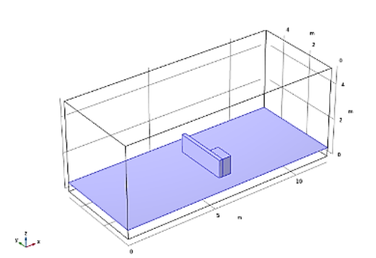

Figure 8. Fixed Wall given by the Shaded faces

2.7 Initial Conditions

Initially, the temperature of the air domain was kept at the temperature at 10AM using the diurnal temperature curve. Relative Humidity was kept at the Ambient Relative Humidity according to ASHRAE 2017. For laminar flow, the initial pressure was kept at Ambient pressure at sea level.

2.8 Mesh Independence Study

A mesh independence study was done using the output as the average temperature of the ground and the wall.

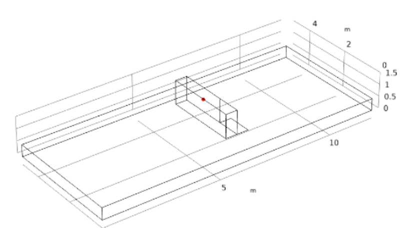

Figure 9. Temperature readings taken at Cut Point 1 (Coordinates 6.5, 3, 1)

Table 2. Selection of Temperature at Cut Point 1 (6.5, 3, 1)

No. of elements	1200	5969	36347
9.00AM	29.66	29.78	29.78
10.00AM	32.70	32.81	32.61
11.00AM	33.80	33.77	33.69
12.00PM	34.60	34.59	34.54
01.00PM	35.25	35.28	35.25
02.00PM	35.83	35.89	35.87
03.00PM	36.34	36.42	36.41
04.00PM	36.78	36.87	36.86

Table 3. Temperature on Different Surfaces

No of elements	Avg Temperature of the Ground at 3PM (ºC)	Avg Temperatur e of the Wall at 3PM (ºC)
1200 (degrees of freedom (DOF) solved for: 23735)	34.514	36.626
5969 (DOFs solved for: 12330)	34.553	36.673
36347 (DOFs solved for: 60759)	34.581	36.68

The mesh setting with 12330 DOFs was used. The results from the model were then used as boundary conditions for the next model's ground and wall temperatures.

2.9 Study Process

A mesh independence study was done for the model simulating the temperature and humidity around the wall, and the mesh consisting of 334584 DOFs was chosen. A stationary study was done for 'Single Phase Laminar Flow'. Then a time dependent study was done for 'Heat Transfer in Moist Air', 'Moisture Transport in Air', 'Heat Transfer in Solids', 'Surface to Surface Radiation' physics with Multiphysics couplings, 'Heat and Moisture' (which couples 'Heat Transfer In Moist Air' and 'Moisture Transport in Air'), 'Moisture Flow' (which couples 'Turbulent Flow' and 'Moisture Transport in Air'), 'Non- isothermal flow'(which couples 'Turbulent Flow' and 'Heat transfer in moist air') and 'Heat Transfer' with 'Surface to Surface Radiation' (which couples 'Heat Transfer in Solids' and 'Surface to Surface Radiation' physics). Temperature and relative humidity readings were taken on the midpoint of the Control wall and the midpoint of the Green Wall as per the experiment done by Jayasundara et al. (2017)

2.10 Approach to validate the numerical model

The numerical values were validated against the experimental data taken from Jayasundara et al. (2017). Their study was intended to assess the impact of green walls on thermal comfort and air quality in urban residential settings. Temperature, relative humidity, and Carbon Dioxide were used as representative parameters in the experiments, and a model of a green wall system was created to assess the effects of various variables. The experiment was conducted on several plants, namely *Tradescathus spathacea*, *Xiphidium caeruleum*, *Sansevieria trifasciata* and *Peperomia obtusifolia*. According to the study, the best-performing plants in terms of lowering temperature and increasing humidity were *Sansevieria trifasciata* and *Peperomia obtusifolia*, respectively. None of the plants had a notable impact on lowering CO_2 levels. The study also discovered that the effect of the green wall could be seen even at 5m away. Overall, the paper sheds light on the potential of detached green walls to improve thermal comfort in urban residential settings. Figure. 10 represents the experimental setup that Jayasundara et al. (2017) conducted experiments on and the results they obtained.

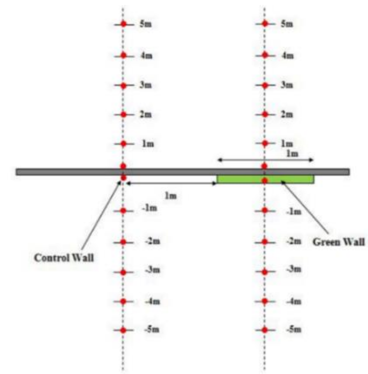

Figure 10. Experimental Setting (Source: Potential of improving air quality and thermal comfort via green boundary walls, Jayasundara K et al, 2017)

3 RESULTS & DISCUSSION

When the results were analyzed, numerical data from where the airflow is from inlet 1 (inlet behind the green wall) showed the most correlation with the experimental results. Figure 11 shows how the temperature of the green wall and bare (cement blocks) wall varied with time for the experimental wall and the simulation wall. The data is for the airflow from the inlet 1. Experimental data shows that the temperatures of both bare wall and green wall increase with time while the green wall temperature is lower than the other by about 2°C. The numerical simulation showed a similar increasing trend for both bare wall and green wall and the gap between the two walls was also similar.

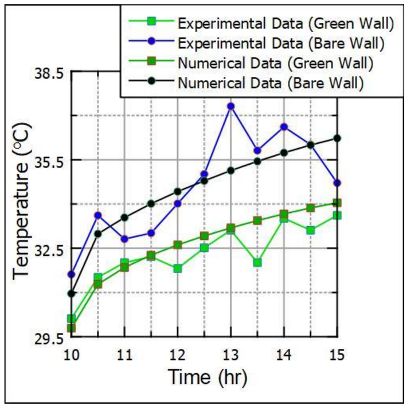

Figure 11. Numerical & Experimental Results for Temperature vs Time

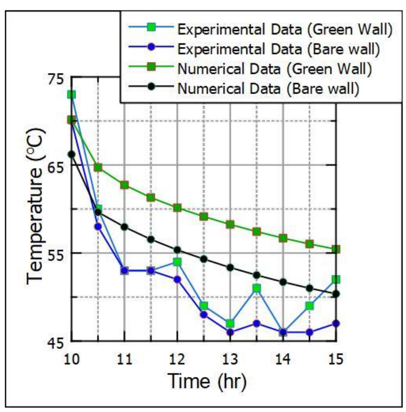

Figure 12. Numerical & Experimental Results for Relative Humidity vs Time

Figure 12 depicts that the variation of Relative Humidity (RH) of the green wall and bare (cement blocks) wall varied with time for the experimental wall and the simulation wall. Both experimental data and simulation data show that the relative humidity of both bare wall and green wall decreased with time. The experimental data for green wall and the experimental data for bare wall showed a close resemblance to each other. This was true for the time dependence variation and actual value. In the case of simulated data, the same trend was observed for both wall types but the relative humidity values were consistently different by about 5%.

In order to verify whether the data from the numerical model and experimental model has similar variance, a two tailed F-test was performed on the numerical values and the experimental values. Table 4 and 5 depict the F-test results for the temperature variation on the green wall and control wall with time.

Table 4 depicts the F-test results testing for the significant difference in variance between the temperature data of the green wall and bare wall. For both wall types, F (lower value) <F<F_(upper value) when α = 0.025, the variance of the two data sets (numerical data and experimental data) do not significantly differ from each other for both wall types (green wall and bare wall). The observed differences among the two groups could be reasonably due to random variations. (Freund, Wilson & Mohr,2010)

Table 4. Results of the F-Test for the differences in temperature variation

	Green Wall		Bare (Cement block) Wall	
	Numerical Data	**Experimental Data**	**Numerical Data**	**Experimental Data**
Mean	32.615	32.309	34.463	34.582
Variance	1.627	1.037	2.411	3.102
Observations	11	11	11	11
Df	10	10	10	10
F	1.569		1.286	
F lower value	0.269048644		0.269048644	
F upper value	3.7168		3.7168	

Previous studies in Sri Lankan context have shown that green areas and walls can reduce temperatures compared to non-vegetated areas and walls. The difference can be up to 2°C (Halwatura & Nishad 2012, Rathnayaka et al 2015). Above findings related to temperature reveal a similar reduction range even when numerical modelling is used. The CFD study done by Widiastuti, R et al (2021) concluded that the vegetated wall can reduce the temperature of indoors by 1.7 ºC. The investigation was done by using numerical simulations. Hosseinzadeh. et al (2022) showed that planting trees close to a building can reduce the air temperature at the ground level by 2-3ºC.

Accordingly, the temperature models developed from the simulation can be used to model the trends of temperature variation of green walls and bare walls.

Table 5 depicts the F-test results testing for the significant difference in variance between the RH data of the green wall and bare wall for numerical and experimental values. Since, F (lower value) <F<F (upper value) when $\alpha = 0.025$, it can be concluded that the variances of the two sets of data (numerical and experimental) do not significantly differ from each other for both wall types (green wall and bare wall).

The present work used a constant wind speed and direction throughout the day. Future work targeting more accurate results can attempt to incorporate the variation of wind direction and speed. The present study used a constant transpiration rate which may vary with the time of the day due to changes to the intensity of the sunlight. Thus, incorporation of variation to transpiration rate could also be recommended as future work.

Table 5. Results of the F Test for the differences in Relative Humidity variation

	Green Wall		Bare (Cement block) Wall	
	Numerical Data	Experimental Data	Numerical Data	Experimental Data
Mean	60.182	53.364	55.359	51.455
Variance	19.185	57.055	21.480	53.273
Observations	11	11	11	11
Df	10	10	10	10
F	2.974		2.480	
F lower value	0.269048644		0.269048644	
F upper value	3.7168		3.7168	

5 CONCLUSION & RECOMMENDATIONS

This study attempted to numerically model the microclimate around vegetated and non-vegetated boundary walls using temperature and RH. The outcomes related to temperature revealed that developed model can be used to predict the trends in temperature variation with time. The model for RH requires further refinement for accurate prediction of RH.

According to the numerical model and the experimental results, green walls can be successfully modeled for temperature using numerical modeling. The proposed numerical model can be used to identify best planting options. The properties and dimensions of the wall, and the greenery to be planted could be varied in the model to see how the temperature near the wall would vary. The model can thus be used to optimize green wall designs without physically constructing a large number of green walls. This eliminates the need to construct and test a number of green walls leading to a substantial saving of time and resources.

Future work can attempt to improve the accuracy of the developed model by incorporation of temporal variations of transpiration rate and wind direction.

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Notations and nomenclature

Symbol	Definition	Unit
C_p	Specific heat capacity at constant pressure	J/(kg·K)
c_{sat}	Saturation concentration of vapor	mol/m^3
c_v	Vapor concentration	mol/m^3
D	Vapor diffusion coefficient in air	m^2/s
$e_b(T)$	Blackbody total emissive power	W/m^2
F	Volume force vector	N/m^3
F_{amb}	Dimensionless Ambient view factor	1
FEP	Fractional Emissive Power	1
G	Surface irradiation	W/m^2
G	Moisture source (or sink)	kg/(m^3·s)
G_{amb}	Ambient irradiation	W/m^2
g_{evap}	Evaporation flux	kg/(m^2·s)
G_{ext}	External irradiation	W/m^2
G_m	Mutual surface irradiation	W/m^2
J	Radiosity	W/m^2
K	Thermal conductivity	W/(m·K)
K	Evaporation rate factor	m/s
L_v	Latent heat of evaporation	J/kg
M_v	Molar mass of water vapor	kg/mol
P	Pressure	Pa
Q	Conductive heat flux	W/m^2
Q	Heat source	W/m^3
q_{evap}	The latent heat source	W/m^2
Q_{ted}	Thermoelastic damping	W/m^3
T	Temperature	K
T_{amb}	Ambient Temperature	K
U	Fluid velocity vector	m/s
Ε	Dimensionless Surface emissivity	1
Ρ	Density	kg/m^3
Τ	Viscous stress tensor	Pa
ϕ_w	Dimensionless Relative Humidity	1

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