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THERMAL SIMULATIONS ON THE EFFECTS OF VEGETATED WALLS ON INDOOR BUILDING ENVIRONMENTS

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ABSTRACT

A simulation study was undertaken to assess the effects of vegetated walls on the thermal performance of a building. A thermal model of climbing plants was formulated using ECOTECT environmental simulation software and was validated against the data obtained by field measurements. This model was applied to a further simulation study and the results showed that plant cover improved indoor thermal comfort in both summer and winter, and reduced heat gains and losses through the wall structure. This resulted in lower annual energy loads for heating and cooling, and these effects were more significant in the case of plant cover on lightweight buildings.

INTRODUCTION

Building integrated greenery was introduced in some cities as part of a strategy to improve the urban environment. While green roofs have quickly spread in today's modern cityscapes, wall greening is yet to establish its own role in urban revegetation as there are technical and economic disadvantages. Vertical greenery has a huge potential of utilising otherwise neglected building surfaces where land is at a premium. However, there have been limited studies conducted on the effect of vegetated walls on the surrounding environment. It is crucial to quantify the benefits of wall greenery for the public and ambient environments to promote the new technology and optimise its potential use.

There have been a growing number of studies to find out the thermal benefit of green walls. Hoyano (1988) examined the shading effect of Ivy cover on a concrete building in Tokyo, with the existence of plants, the external surface temperature of the west facing wall was reduced by 18% and the indoor air temperature by 7°C. The results of the extensive field experiments led by Nojima and Suzuki (2004) in Tokyo also indicated the lower temperature of external wall surfaces as well as the reduction of conduction heat gain by plant cover. Vegetation decreased heat transfer through the south facing wall by 13.7% to 40.7%. The effects were more significant when the indoor space was air-conditioned and in the case of a building of lighter construction. Eumorfopoulou and Kontoleon (2009) observed a cooling effect of climber cover on both sides of wall surfaces and indoor air in the Northern part of Greece. It was recorded that vegetation kept a daily room temperature 2°C cooler on average. The experiments were carried out by Cheng et al in Hong Kong. (2010) on living wall modular panels which consisted of a substrate layer that plants rooted within. When the room was air conditioned at 26°C, the panels reduced the daily cooling load by 1.45kWh and the internal wall surface temperature by 2°C.

Along with experimental studies, a few simulation methods have been explored to evaluate the thermal impacts of vegetated walls. MacPherson (1988) simulated the energy performance of a residential model in four selected climates in the U.S. using the energy analysis program MICROPAS. In this study, the plants on the west wall were found to be the most efficient in reducing cooling loads and the south and east in reducing the heating loads. Holm (1989) conducted a similar study using the DEFOB system and the vegetation model of a climber was validated against the result of experimentation. It was indicated that the vegetation cover had a larger effect on the indoor temperature of low-mass buildings. More sophisticated simulations using CFD analysis tool were conducted later by Handa et al. (2007, cited in Suzuki, 2008). A town model of an existing area in Tokyo was recreated within the program. The area temperature was decreased by maximum 2°C when the surfaces of the roof, south and west walls of buildings were covered by greenery. Bass (2007) calculated potential energy savings of green walls in the cold period in Toronto using the Urban Forest Effects (UFORE) modelling software. The green wall showed the insulation effects and reduction of wind chill. Rosenlund et al. (2010) also looked at the effects in the cold climate in Malmö, Sweden using Energy Plus, the program that includes a physical model of green roofs. No significant impact was shown on building energy performance when it was insulated to current Swedish standards and 3kWh/m^2 savings by green wall was calculated on a building model without insulation.

In the present paper, the results of the simulation study were analysed in order to seek an understanding of long-term effects of vegetated walls in improving building thermal performance and indoor thermal comfort.

SIMULATION

Simulation program

The environmental simulation software ECOTECT was used in this study. The software was chosen for the function that allows the user to apply thermal properties to individual building components so that accurate thermal performance of materials can be calculated.

Vegetation model

At first, a thermal model of Hedera helix (Common Ivy) was created within the simulation program. The result of a field study conducted by Nojima, et al. (1993) was used for validation of this model. In this study, the monitored wall was covered by climbers Lonicera, Japonica and Trachelospermum Asiaticum. The plants consisted of several components such as foliage, woody stems, air gap and water vapour that is similar to Ivy. All the physical properties of these components were reflected in the calculation of thermal performance of climbing plants.

Thermal property of Ivy leaves applied to a model:

- Specific Heat: 2.8 J/kgK
  (Moore and Fisch, 1986)
- Thermal Conductivity: 0.36 W/mK
  According to the data measured on leaves of Eucalyptus globules (Hays, 1975)
- Density of leaf layer:
  1000mm/0.3mm *200 *0.8g = 533,280g/m^3
- Estimated leaf area of English Ivy:
  0.005m2/leaf (200leaves/m^2)
  Weight of Eucalyptus globules leaf: 0.8g
  Thickness of Eucalyptus globules:0.3mm (Hays, 1975)

Referring to the simulation model of plant cover by Holm (1989), the vegetation model consisted of three different elements, leaf, stem and air gap. Figure 1 shows the construction of climber cover. Softwood with a thickness of 15mm represents stems of Ivy and the density of the softwood (550Kg/m^3) was reduced by 80% to make it equivalent to 20% stem mass within the layer. Water vapour was added to correspond to evaporated water from leaves.

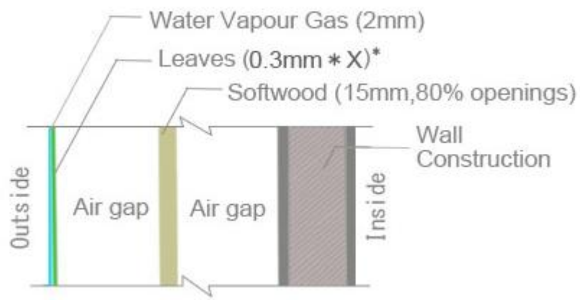

Figure 1
Section of a thermal model of climber covering wall

Table 1
Thermal properties of model components

Layer Name	Width (mm)	Density (Kg/m^3)	Sp. Heat (J/KgK)	Conduct. (W/mK)
Water Vapour	2.0	0.6	1966	5.56
Leaves	0.3 X*	533	2.8	0.4
Air Gap	T**	1.3	1004	5.56
Softwood (Stem)	15	110	1880	0.14
Air Gap	T**	1.3	1004	5.56

* X= Covering ratio by Ivy leaves (Hoyano, 1988)
** T= Plant cover thickness/2

Validation of a vegetation model

To validate this vegetation model, a test cabin used in the field experiment led by Nojima et al. (1993) was recreated within the software. The experiment was conducted on the cabins built in Tukuba situated 50km north of Tokyo in summer in 1995. A south facing wall of the cabin was constructed with 4.7mm Asbestos Cement Board and a part of the wall was covered by climbers that had grown to approximately 500mm thickness. Internal wall surface of other orientations, ceiling and floor were insulated by glass wool to reduce heat transfer through these surfaces.

The Internal space of the cabin model was divided into three thermal zones according to the experiment including Exposed Room (Non-vegetated), Vegetated Room and Non-Examined space. The annual weather data of Tokyo was imported from Energy Plus and two hot days that weather conditions were comparative to the measurements were selected for validation. Due to a lack of weather information, the simulation results were not identical to the field measurement. However, both recorded and simulated data showed that vegetation kept the indoor air temperature cooler than outside in the daytime while the Exposed room was overheated and stayed 5.9°C (experiment) and 5.5°C (simulation) warmer than outside on the bright hot day. The maximum indoor temperature of Vegetated room resulted in 6.1°C (experiment) and 5.3°C (simulation) lower compared to the Exposed room. At night, the simulation result showed the room temperature with exposed wall dropped rapidly after sunset and stayed slightly cooler than the room with a vegetated wall, this was also correlative to the recorded data.

Applied simulation on a residential building

The validated vegetation model was then applied to further simulations to investigate the effect of climber covered walls in the temperate climate (Tokyo, Japan). A model of a standard two bedroom residence was used for this study, one story building consisted of four main thermal Zones that were located at each corner of the building (see Figure 2).

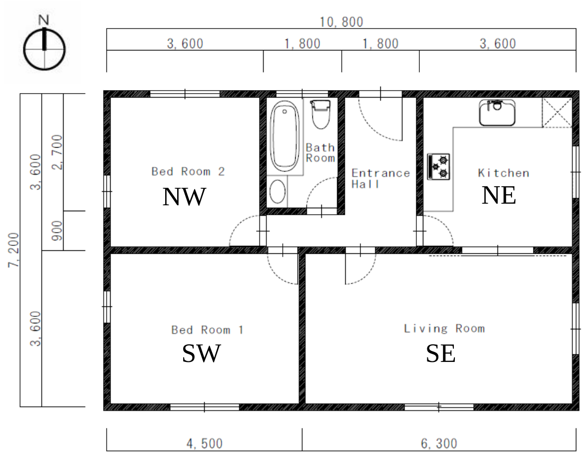

Figure 2
Floor plan of the simulation model and orientation of simulated rooms

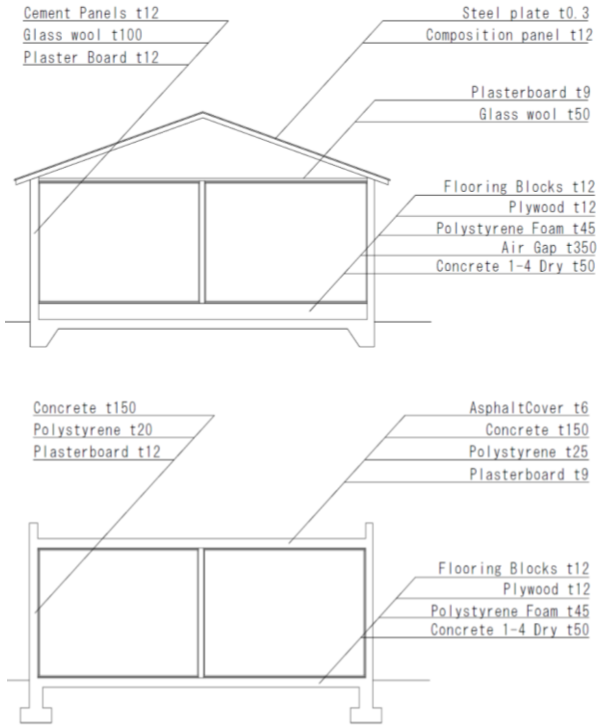

Figure 3
Construction of Lightweight model (Top) and Heavyweight model (Bottom)

The simulations were conducted on building models of two different construction materials, one was heavy (reinforced concrete) and the other was lightweight (timber framed). The software calculated that 250mm climber cover reduced U-value of a lightweight wall from 1.24 to 0.69 (W/m^{2}K) and heavyweight from 1.16 to 0.68 (W/m^{2}K). Thermal settings of each Zone (room) of the building were determined based on a practical usage as a private residence with four occupants and the weather data of Tokyo was imported form Energy Plus.

Table 2
Construction and thermal properties of a lightweight building model

	Layer Name	Width	Density	Sp.Heat	Conduct.
1.	Water Vapour Gas	2.0	0.6	1966.000	5.560
2.	vegetation	1.0	533.0	2.800	0.400
3.	Air Gap	125.0	1.3	1004.000	5.560
4.	Softwood	15.0	110.0	1880.000	0.140
5.	Air Gap	125.0	1.3	1004.000	5.560
6.	Cement Panels, Wood F	12.0	400.0	1470.000	0.120
7.	Wool, Fibrous	100.0	90.0	820.000	0.200
8.	Plaster Board	12.5	1250.0	1088.000	0.431

Table 3
Construction and thermal properties of a heavyweight building model

	Layer Name	Width	Density	Sp.Heat	Conduct.
1.	Water Vapour Gas	2.0	0.6	1966.000	5.560
2.	vegetation	1.0	533.0	2.800	0.400
3.	Air Gap	125.0	1.3	1004.000	5.560
4.	Softwood	15.0	110.0	1880.000	0.140
5.	Air Gap	125.0	1.3	1004.000	5.560
6.	Concrete Cinder	150.0	1600.0	656.900	0.335
7.	Polystyrene	20.0	1050.0	1423.000	0.126
8.	Plaster Board	12.5	1250.0	1088.000	0.431

RESULTS AND DISCUSSION

For investigating the thermal impact of vegetated walls depending on their orientation, simulations were carried out on models with all exposed walls and vegetation on one of four external surfaces respectively. The study was focused on interior temperatures, passive heat gains and losses, and heating and cooling loads of the building.

Indoor air temperature

For simulations of indoor air temperature, all the rooms were set to be naturally ventilated for 24 hours in order to eliminate the influence of mechanical air conditioning on the room temperatures. The simulation results showed that plant cover helped to stabilise the room temperature regardless of orientation and seasons by reducing solar radiation gains in the daytime and conduction heat losses at night.

As the north surface of the building did not receive direct sunlight, the effect of plant cover on this orientation was insignificant on indoor temperature in summer. On the other hand, north facing vegetation kept Zone NW and NE warmer throughout the day during the winter period.

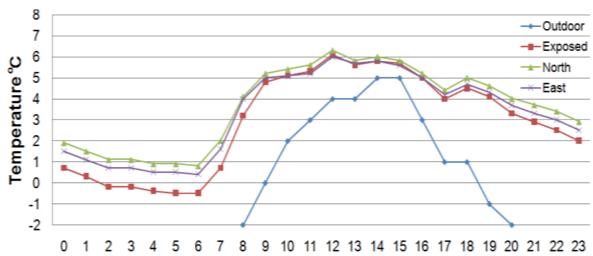

Figure 4
Hourly indoor temperature of NE on the coldest day (Lightweight construction)

Whilst Climbers on the east surface had little effect on the indoor temperature, Figures 5 and 6 show that vegetation on the south wall kept the daytime temperature of Zone SW lower by reducing the solar heat gain throughout the year. This had a negative effect in winter although plants insulated the wall at night. The figures of west facing vegetation showed similar effects to the south in summer, however in the cold period, it had a favourable effect throughout the day and kept the nighttime indoor temperature of Zone SW warmer by 0.4-0.9°C compared to the room without plant cover. The figures also showed the temperature of Zone SW when both external walls were covered by climbers. Applying vegetation on the south and west surface appeared to be the most effective in reducing fluctuation of the indoor temperature range in both summer and winter.

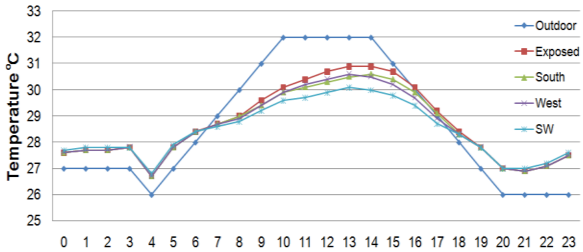

Figure 5
Hourly indoor temperature of SW on the hottest day (Lightweight construction)

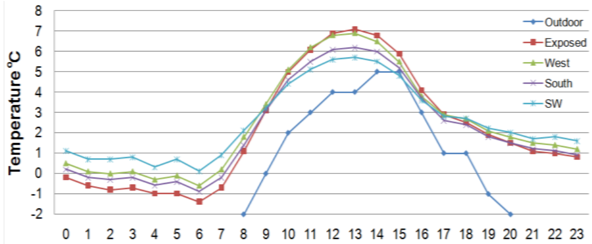

Figure 6
Hourly indoor temperature of SW on the coldest day (Lightweight construction)

The simulation results of the heavyweight model showed similar effects to the lightweight, although differences of the indoor temperature between vegetated and non-vegetated rooms were less significant. The following figures show indoor temperature increments and decrements resulting from the absence of vegetation cover in Zone SW (see Figures 7 and 8). Climber cover on south and west surface reduced the maximum indoor temperature of the lightweight model by 0.9°C on the hottest day and increased the minimum temperature by 1.7°C on the coldest day. In the case of the heavyweight model, the maximum temperature was reduced by 0.5°C and minimum temperature was increased by 0.4°C. The figures indicate that vegetation on lightweight construction had unfavourable effects at nighttime in summer and in the daytime in winter. Both negative and positive thermal impacts on lightweight construction were amplified compared to the heavyweight.

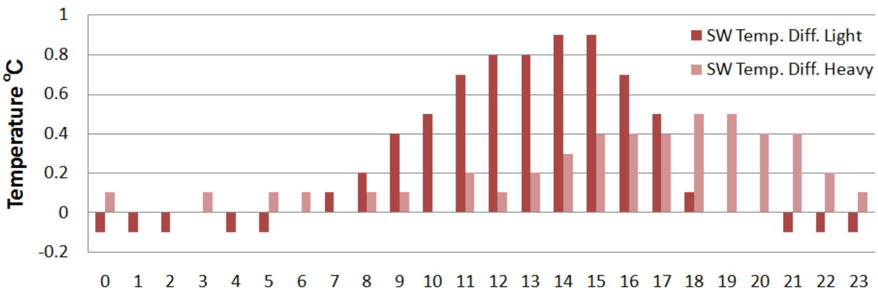

Figure 7
Hourly indoor temperature differences of Zone SW on the hottest day (Lightweight and Heavyweight)
$T_{exposed}$-$T_{vegetated}$

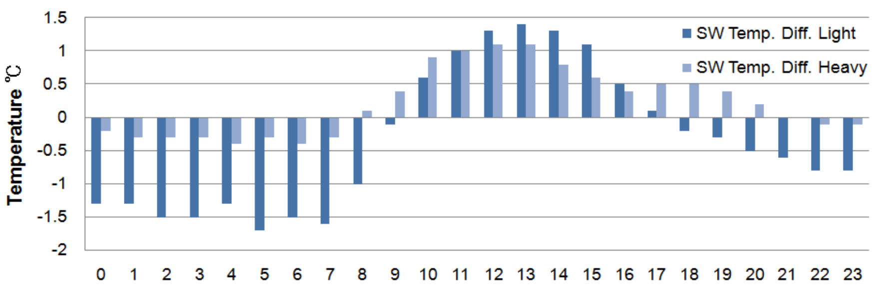

Figure 8
Hourly indoor temperature differences of Zone SW on the coldest day (Lightweight and Heavyweight)
$T_{exposed}$-$T_{vegetated}$

Passive heat gains and losses

For this study, four thermal Zones were set up to be ventilated, air conditioned and heated, and the bathroom to be ventilated and heated to keep indoor air temperature within a comfortable range of 18-26°C. Figures 9 and 10 show the breakdown of passive heat gains and losses. Heat exchange was divided into two types, one Solar (direct and indirect) and Fabric (Conduction), the other internal (occupants, equipment and in between adjacent zones) and ventilation. The figures indicated annual breakdowns of Zone NE and SW of the lightweight model in four different situations when no climber cover was applied (exposed) and one of the external walls or both were vegetated.

The vegetation on the single wall surface reduced annual conduction heat gains between 7.3% & 24.5% and heat loss between 17.4% & 24.1%, these effects were much greater when plants covered both external walls. Despite the higher reduction rates of heat gain through the north-facing wall, vegetation on south and west had more impact on the indoor thermal environment as the initial amount of conduction gain through these walls would be much greater. The results of heavy weight construction showed almost identical effects although the reduction of conduction gains and losses were relatively smaller compared to the lightweight construction.

Energy loads for heating and cooling

The simulation result of heating and cooling loads showed that vegetation cover contributed in reducing energy requirements for indoor thermal comfort.

Tables 4 and 5 show the results of calculation on annual energy loads for an entire building using two construction models with no vegetation (exposed), vegetation on south and west facing walls and vegetation on all external walls around the building (fully vegetated).

Table 4
Annual energy loads for heating and cooling (Lightweight model)

	Exposed	SW Vegetated	Fully Vegetated
Heating	3366	2466	1946
Cooling	499	383	350
Total	3865	2849	2296
Savings		1016 (26.3%)	2296 (40.6%)

Table 5
Annual energy loads for heating and cooling (Heavyweight model)

	Exposed	SW Vegetated	Fully Vegetated
Heating	1746	1519	1353
Cooling	227	202	184
Total	1973	1721	1537
Savings		252 (12.8%)	436 (22.1%)

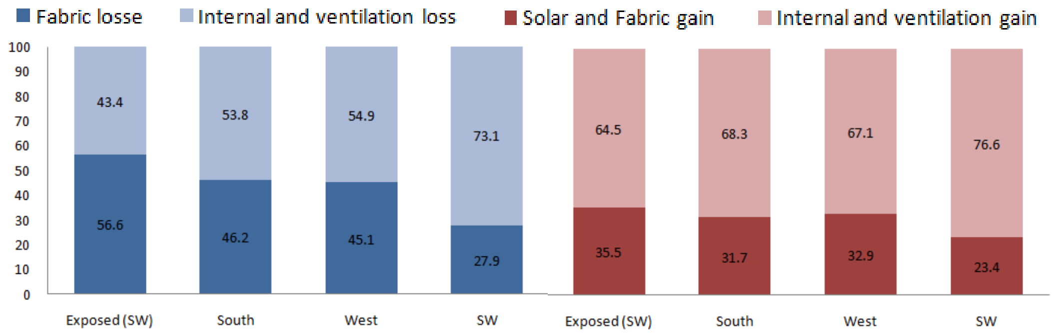

Figure 9
Breakdown of annual passive heat gain and loss Zone SW (%)

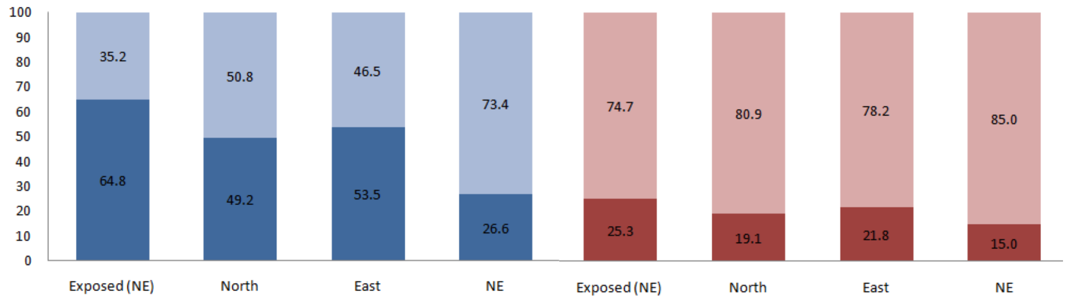

Figure 10
Breakdown of annual passive heat gain and loss Zone NE (%)

The reductions of cooling loads were not substantial in both cases as the initial figure of no vegetated model was very small. Both heating and cooling loads of lightweight building were nevertheless reduced by approximately 25% when south and west surfaces were vegetated and 30% to 40% when vegetated fully. Figures of heavyweight model including energy loads and the reduction rates were nearly half of the lightweight results.

CONCLUSION

The simulation results showed vegetation on external walls stabilised the indoor air temperature of buildings by mitigating daytime solar heating and insulating the wall at night in both hot and cold climates. This trend was also observed in field experiments by Nojima and Suzuki (2004), and Eumorfopoulou and Kontoleon (2009). Plants on south or west walls appeared to be the most effective to decrease daytime indoor room temperature in summer. In cold conditions, the foliage layer increased the minimum temperature when it was applied on the north and west facing walls. Vegetation could also have negative effects such as increasing the nighttime indoor temperatures in summer and obstructing daytime solar heating in winter.

Vegetation also reduced the conduction heat gains and losses through external walls. This resulted in lower energy loads for mechanical heating and cooling.

The simulation results showed that the effects were more significant in the case of plant cover on lightweight buildings than heavier construction. This is corresponding to the values observed by Nojima and Suzuki (2004).

Limitation of the study

It is challenging to create a computational model of vegetated walls that reflect the aspects of the random quality of living plants. Each construction material can only have eight components in the software that means some elements such as layers of leaves had to be assigned as a thick material without air gaps between them. All components were also in a form of layers stuck against each other, this does not represent the horizontal air movement within the vegetation layer that occurs in reality. The validation of the simulation model was limited as the weather data used in the study was not identical to the record of previous studies and there was a lack of physically measured data for a comparative analysis.

Further research

Further field experiments are necessary in order to obtain quantitative data to validate the computer simulation. The physically measured data can be reflected to the simulation model of vegetation which will increase the accuracy of calculation.

The simulation can be applied for buildings in different climates; the results indicated the potential of vegetation for providing winter insulation, this aspect can be explored further as most green wall studies have been focused on summer heating mitigation.

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