Experimental Design of Energy Performance Simulation for Building Envelopes Integrated with Vegetation

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Abstract

Green façades have many benefits, yet few software tools or methods have been developed for architects to assess the quantitative energy performance of green façades. This work-in-progress paper explores the methodologies of modeling and simulating the effects of green façades on wall surface temperatures. It proposes a partially parameterized workflow to compute the thermal performance of green façades within a platform based on Rhinoceros® (Robert McNeel & Associates, Seattle, WA) and its plug-ins. By calibrating the computed results with field measurements, the paper identifies the need for accurate information about vegetated covers and growth rates in modeling a green façade's performance. Also, the paper identifies evaporative cooling from the vegetation's transpiration as a key component contributing to cooling.

1. INTRODUCTION

Green façades, systems in which climbing plants are used to cover building walls, are known for their benefits in saving energy and moderating temperature in dense urban enviornments (Köhler 2008; Hunter 2014). Several studies have been conducted to quantify the thermoregulatory benefits of green façades (Alexandri and Jones 2008; Wong et al. 2010). However, these methods and software are not tailored to architects. In response, this paper explores a new methodology for using Rhinoceros along with its energy performance simulation plug-in, DIVA-for-Rhino (Solemma, LLC, Cambridge, MA, U.S.A.), to model the cooling effects of vegetation on wall surface temperature.

DIVA-for-Rhino is built on RADIANCE, a backward ray-tracer extensively studied since the late 1990s (Ibarra and Reinhart 2009), and EnergyPlus, developed by the U.S. Department of Energy to perform energy simulation for residential and commercial buildings. DIVA-for-Rhino can be used with Grasshopper™ to allow a fully parameterized simulation workflow. At this stage of the project, however, DIVA-for-Rhino's plug-in is used with Rhinoceros to take advantage of simulation metrics such as point-in-time illuminance. This particular metric allows the level of light to be measured at a specific date and time (Lagios 2014). The computed results from this metric can be compared with onsite measurements, allowing more precise calculations of shading effects in energy modeling. Furthermore, vegetated cover is said to be the key trait of the climbing plant in providing cooling effects (Koyama et al 2013). Visualizing the physical geometry of the leaf coverage would not only better assist designers in perceiving the formal quality of the green façade, but would also allow further simulation studies to be quickly done using architect-friendly simulation software.

2. METHODOLOGIES

2.1. Empirical data source and constraints.

The green façades investigated in this study are established by the Green Roof Innovation Testing (GRIT) Lab, which is located on the roof of the five-storey John H. Daniels Faculty of Architecture, Landscape and Design building at the University of Toronto St. George Campus in Toronto, Ontario. Six south-facing 3D greenscreen® façades are built against a building wall containing heated office and storage space. The trellises are 2.15m in height and set away from the exterior wall (MacIvor et al. 2013). The green façades contain Virginia creeper (Parthenocissus quinquefolia) and are set up along with two other green façades of the same modular width (1219mm), covered in River Bank Grape and Nugget Hops respectively. Each green façade has a corresponding control wall, which also has the same width but is free of vegetation on the trellis. This project uses the green façades covered by Virginia creeper, which has been studied across the globe for its cooling effects on building surfaces (Ip, Lam, and Miller 2010).

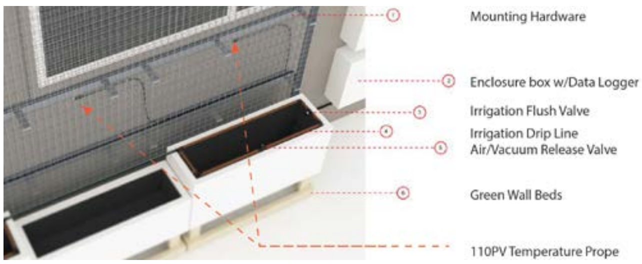

Figure 1. The thermal sensors, irrigation flush valves and green façade beds, and data logger for the green façade (Courtasy of GRITLAB 2013).

A single temperature probe (110 PV Surface Mount Thermistor, Campbell Scientific) was attached to the surface of the exterior wall, centered on both the control and vegetated façades. It measures the wall surface temperature, which is considered the sol-air temperature (Figure 1). In addition to the wall's surface temperature, the GRITLAB records weather data every five minutes. Although the output from all electronic probes is ample, this study is constrained by the frequency of field observations, which include photographic documentation of the vegetated cover and thermograph documentation of the wall surface temperature. So far, there are ten sets of data gathered between the end of May to the end of July. Each set of data consists of the following: the shaded and controlled wall surface temperature (a.k.a. sol-air temperature) recorded by the 110PV Temperature Probes; the shaded wall's surface temperature recorded from the FLIR thermographs taken of a 1x1 m section of the green façade surface at 1 p.m. every five to seven days; and a photograph of the 1x1 m section taken every five to seven days. These ten sets of data form the calibration data set for the following simulation results.

The simulation procedure starts with extracting pixel points from the field observation photographs to construct a series of simplified 3D models of the shading geometry in Rhinoceros. We first use Grasshopper to prepare an algorithmic definition to form points on a 1x1 m plane in Rhinoceros. These points correspond to the position of the pixels that share a given range of the RGB values of the documentation photographs. Then, we use the Eyedropper Tool in Adobe Photoshop (Adobe System Inc., San Jose, CA, U.S.A.) to survey the desired RGB values of the leaves on the documentation photographs. We take these RGB values from Photoshop as the inputs for the "given range of RGB values" in the Grasshopper definition. The algorithmic definition identifies the positions of points, which are matched with the pixels that share the values within the range of RGB values mentioned above. Still in Grasshopper, we construct circular surfaces, which are centred to these points with a desired radius so that any neighbouring circles are approximately tangent to each other.

In order to proceed to daylight simulation analysis with DIVA-for-Rhino, these circular surfaces are "baked" into the shading geometry. Grasshopper's "bake" component transforms the parametric form into a NURBS geometry that is permanent. More importantly, after "baking", the NURBS circular planes, an abstraction of the leaves on the green façade, can be assigned different RADIANCE material definitions to emulate the actual transparency of the leaf. However, at this stage in the investigation, we treated the leaf to be opaque to simplify the simulation procedure.

We first load the weather data, which is downloaded from the EnergyPlus Energy Simulation Software webpage (U.S. Department of Energy, 2013). The simulation metric is set to illuminance with the unit of Lux under Daylight Grid-Based analysis for Point-in-Time Illuminance. The date in the simulation setup will be set according to the date of the field observation photograph and thermograph recording. The time, in general, is set to 1 p.m., because eight of the ten thermographs were taken around 1 p.m. The amount of illuminance received by the wall behind the shading geometries is calculated by implementing these setup procedures for the ten distinct shading geometries, By considering the wall material with a relatively light colour (by choosing a value for α/h_o), a computed sol-air temperature value T_e, measuring the shaded wall surface temperature between the wall and the green medium is obtained by using the equation below.

$$T_e = T_o + (\alpha/h_o) \times (I_t) - (\epsilon/h_o) \times (\Delta R)$$

I_t = illuminance received the wall behind the green medium (lux) x (0.0079 $W/m^2/lux$)*

* Approximation for conversion from the illuminance of sunlight to Solar Radiant flux or Solar Irradiance (Chua, 2013)

$\alpha = 0.75$, $h_o = 17\ W/(m^2\ {}^0C)$ (Hutcheon and Handegord, 1995)

2.2. Comparison and Calibration

The polynomial trendlines in Figure 2 illustrate that the computed T_e values are quite close to the T_e values measured from the 110PV Temperature Probe for the 1x1 m shaded wall surface. However, it is noticeable that the computed T_e values are lower than the measured ones most of the time, especially for values before June 25th when the temperature is relatively cool. This shows that the reduction in wall surface temperature by shading is exaggerated. Koyama and his colleagues pointed out that the overall reduction in wall surface temperature by green façades is mainly contributed by two parts: the interception of solar radiation by the vegetation as well as the cooling effect by the evaporative cooling of the vegetation's transpiration (Koyama et al. 2013). The computed T_e values only account for the first component: the solar radiation interception. Therefore, the computed T_e values should be larger than the measured ones, at least for a significant portion of the observation period. The computed T_e values are directly proportional to the amount of illuminance that the wall received, and inversely proportional to the density of the shading geometry generated by the Grasshopper definition. It is clear that we need to calibrate the Grasshopper definition in processing the field observation photographs.

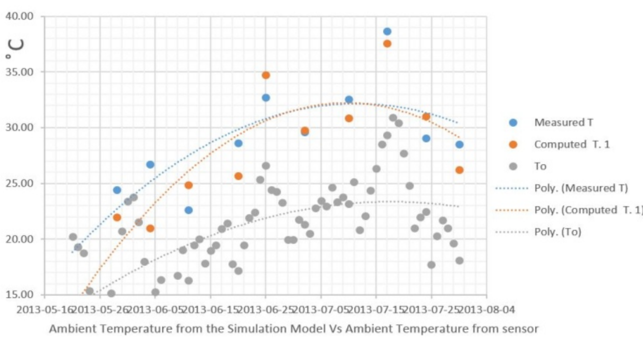

Figure 2. The computed Te vs. the measured Te vs. daily average T.

The Grasshopper definition is changed by replacing the intake field observation photograph with a binary image processed from the original photograph in Photoshop, and by narrowing the range of points accepted to generate the shading geometry. As illustrated in Figure 3, the slider component in the middle of the image is changed to 0.1, which limits most of the deviation from the black colour with RGB values of 0, 0, 0. This generates points with high fidelity to the selected black colour, avoiding over-estimation of the effect of interception of solar radiation by the vegetation. After adjusting the Grasshopper definition, the new set of circular surfaces—shading geometry—will be "baked" from Grasshopper for the second round of daylight simulation analysis with DIVA-for-Rhino as stated above.

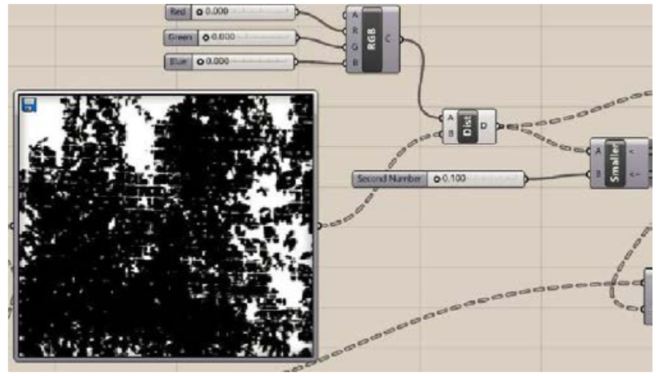

Figure 3. The binary image in Grasshopper to generate less dense shading geometry.

3. CONCLUSION

The calibrated illuminance values from the second-round DIVA point-in-time daylight simulation analysis generated higher T_e values, as shown in Figure 4. Compared to Figure 2, the newly computed T_e values show that the interception of solar radiation by the leafiness of vegetation will not be the only dominant factor in providing cooling to the wall surface, as the values on the computed T_e's trendline are higher than the ones on the measured T_e's trendline. As Price remarks, the percentage of cooling effect that could be maximally contributed by evapotranspiration is estimated to be 47%, which means 53% of the cooling effect is achieved by shading on a south-facing green façade in mid-Atlantic weather (Price, 2010). In these calibrated results, for instance, on June 25th, the ΔT between the control and computed wall surface temperatures is 2.68°C, which is 51.4% of the ΔT between the control and the measured wall surface temperatures—5.49%. In short, using DIVA-for-Rhino and the shading geometry generated from a given empirical field observation can produce a reasonably reliable estimation only of the effects that vegetation's shading has on the overall thermal performance of a green façade during hot summer days.

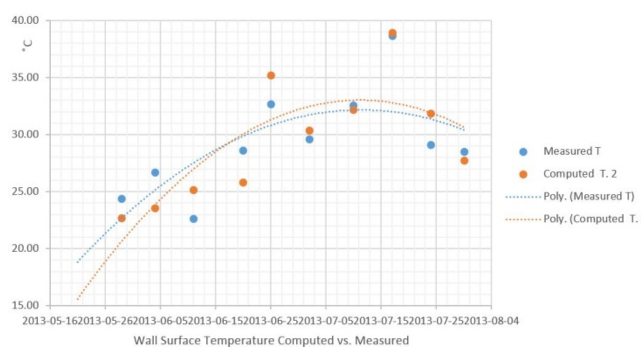

Figure 4. The computed Te vs. the measured Te.

In short, using DIVA-for-Rhino and the shading geometry generated from a given empirical field observation can produce a reasonably reliable estimation only of the effects that vegetation's shading has on the overall thermal performance of a green façade during hot summer days.

4. NEXT STEP

Although the calibration work has been performed and the shading geometry is more accurate, a large portion of the trendline of the computed shaded wall surface temperature during June and July is lower than the wall surface temperature measured on site. The downloaded weather file used in the simulations above was recorded at the airport, which is cooler than downtown Toronto due to the urban heat island effect noted by GRITLAB's weather records. This suggests that one should load a local weather file collected onsite to run the simulations in future studies. Also, the over-estimation of plant leaf size and its shading effect on the wall surface requires attention. It urges our future research to look into two areas: understanding the mathematical models of the growth rate of the plant, and finding an appropriate combination of RADIANCE material definitions to represent seasonal changes in the transparency of the vegetated cover. This could minimize human error and the constraints imposed by the observation frequency in the current empirical approach. For instance, the vegetated cover for vine plants is determined by the vine length (Koyama et al. 2013). If this relationship is modeled into a fully parameterized Rhinoceros-Grasshopper platform, the simulation can achieve higher accuracy in computing the plant's interception of solar radiation at any point in time. The modeling of evaporative cooling by plant transpiration is also crucial in order to achieve a complete simulation for the cooling effect of vegetation. Once these unknowns are resolved, one can apply the computed shaded wall surface temperature into DIVA-for-Rhino's Thermal Analysis, in which the indoor temperature of a structure with a vegetation-integrated envelope could be computed. Since most of the workflow stated above could be done in one single platform, Rhinoceros, this future works aligns with the objective of developing a reliable parameterized simulation workflow for computing the thermal performance of green façades.

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