The Pennsylvania State University
The Graduate School
Department of Architectural Engineering

PREDICTIVE HEAT AND MASS TRANSFER MODEL OF
PLANT-BASED ROOFING MATERIALS FOR
ASSESSMENT OF ENERGY SAVINGS

A Dissertation in
Architectural Engineering

by

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ABSTRACT

Green roofs are becoming popular in the U.S. with the green roof industry growing at a rate of 30-50% from 2001 to 2008. Green roofs are a sustainable technology that could potentially offer several benefits to society and the environment. There have been several models proposing different ways to represent models of green roof systems. Until now, none of these models have been properly verified and validated. Moreover, to the best of our knowledge, there is no single study that has measured all of the important heat and mass transfer processes simultaneously.

Thus, the overall objective of this thesis is to develop a predictive heat and mass transfer model for green roof systems in summer conditions. The model is also verified and validated with experimental data from the “Cold Plate,” an experimental apparatus specifically designed and built to quantify heat and mass transfer processes. The “Cold Plate” apparatus represents a new kind of apparatus that addresses the shortcomings in the existing data sets on energy balance for green roofs. Experiments were conducted in a full-scale environmental chamber that simulated outdoor conditions. Currently, there is no other experimental apparatus that simultaneously measures the same physical phenomena.

Overall, more than 10 experiments were conducted inside the environmental chamber. Evapotranspiration had the role of controlling the intensity of all other heat fluxes by modulating or diverting incoming and outgoing heat fluxes, depending on the state of the plants and environmental conditions. Interestingly, the lowest conductive heat fluxes through the green roof were consistently found when the green roof was the wettest. This finding also addresses the old dilemma regarding the tradeoffs between having a dry or a wet green roof.
A new green roof model is proposed. The model considers heat and mass transfer processes between the sky, plants, and substrate. Based on laboratory experimental data collected in the “Cold Plate” apparatus, a new substrate resistance to soil evaporation is introduced. Moreover, previous functions to calculate plant resistance for transpiration calculation are evaluated and the functions that best approximate the measured values are selected. These two steps are important for correct evapotranspiration calculations and have not been done previously.

Finally, the new green roof model is validated using quasi-steady state experimental data from the “Cold Plate.” The validation shows that the model tends to predict most of the heat and mass transfer appropriately, but tends to underestimate maximal evapotranspiration. Further research on convective heat transfer on plants is recommended, as well as a spectral reflectivity measurement of the substrate to improve the accuracy of the model. The final step before model implementation into a building energy simulation will be a dynamic validation using detailed laboratory and field data.
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NOMENCLATURE

e_{air} = vapor pressure of the air

e_s = vapor pressure at the evaporative surface

e_{s,PM} = vapor pressure of the air

e_{so} = vapor pressure of the air in contact with the surface

ET = evapotranspiration, or latent heat flux

f(u) = function of the wind speed

h_{convection} = convective heat transfer coefficient

h_{heat} = heat transfer conductance

h_{sub} = substrate convective heat transfer coefficient

i_g = enthalpy of vaporization

k_{plants} = thermal conductivity of leaves

k_{por} = thermal conductivity of porous media

k_s = extinction coefficient

LAI = leaf area index

M = metabolic storage (photosynthesis and respiration)

Nu = Nusselt number

Nu_{por} = Nusselt number for porous media

P = atmospheric pressure

Pe = Péclet number

Q_{IR,substrate,sky} = thermal radiation or radiative heat exchange between substrate and sky

Q_{substrate} = conductive heat flux through green roof substrate

Q_{conduction} = conductive heat flux through roof

Q_{film} = Q_{convection}+Q_{IR}+Q_{Evaporation}

Q_{film,plants} = Q_{convection}+Q_{IR}+Q_{T}
\( Q_{\text{IR}} \) = radiative heat transfer between the plant layer and the top substrate layer
\( Q_S \) = convective heat transfer between the top substrate layer and the surrounding air
\( Q_{\text{sensible}} \) = convective or sensible heat flux
\( r_a \) = aerodynamic resistance
\( r_a \) = aerodynamic resistance to mass transfer
\( r_a \) = aerodynamic resistance
\( z_m \) = height of wind measurements
\( z_h \) = height of humidity and temperature measurements
\( d \) = zero plane displacement height
\( z_{om} \) = roughness length governing momentum transfer
\( z_{oh} \) = roughness length governing transfer of heat and vapor
\( k \) = von Karman's constant, 0.41
\( u_z \) = wind speed at height \( z \)
\( R_{\text{conv}} \) = Resistance to convective heat transfer
\( R_l \) = Resistance to latent heat transfer
\( R_{\text{IR}} \) = Resistance to thermal radiative heat transfer
\( r_l \) = stomatal resistance of the well-illuminated leaf
\( e_{so} \) = saturated vapor pressure at the soil temperature
\( R_n \) = net radiative flux
\( R_{n,IR} \) = long-wave or thermal infrared radiation from the surroundings
\( R_{n,solar} \) = short-wave or solar radiation (direct and diffuse)
\( r_s \) = stomatal resistance to mass transfer
\( R_{sh} \) = solar or short wave radiation on the surface
\( R_{sh,abs} \) = Absorbed solar radiation by the green roof substrate
\( R_{sh,abs,plants} \) = absorbed short wave or solar radiation by the plants
\( R_{sh,abs,substrate} \) = absorbed solar radiation by substrate underneath the plants
\( r_{soil} \) = soil surface resistance to mass transfer
$S_{\text{thermal}} =$ thermal storage for substrate, plants

$T_{\text{leaf}} =$ leaf temperature

$T_{\text{sky}} =$ sky temperature

$T_{\text{top,substrate}} =$ substrate temperature

$\alpha =$ relative humidity of air at the land surface

$\alpha_{\text{leaf}} =$ albedo or reflectivity of the leaves

$\alpha_{\text{soil}} =$ albedo or reflectivity of the soil

$\beta_{\text{soil}} =$ moisture availability parameter = \[ \frac{r_a}{r_a + r_{\text{soil}}} \]

$\gamma =$ psychrometric constant = $C_p P/0.622i_f \gamma$

$\phi =$ porosity of plant layer

$\Delta =$ slope of the saturation vapour pressure, \[ \Delta = \frac{4098e}{(T + 237.3)^2} \]

$\varepsilon_{\text{leaf}} =$ emissivity of the leaves

$\varepsilon_{\text{soil}} =$ emissivity of the soil

$\sigma =$ Stefan-Boltzmann constant, $5.64 \times 10^{-8}$ W/m²K⁴

$\sigma_f =$ plant coverage of the green roof

$\tau_{\text{plants,IR}} =$ long-wave transmittance of a canopy

$\tau_{\text{plants,solar}} =$ shortwave transmittance of a canopy
I would like to express my sincere gratitude to my advisor, Dr. Jelena Srebric, for her support, help and friendship. She always encouraged and guided me during difficult as well as during good times. Moreover, she was always available and willing to help during and beyond office hours. I would also like to thank my committee members: Dr. Stanley Mumma for sharing his expertise and passion about HVAC systems and for always being willing to help; Dr. Bohumil Kasal for his critical thinking and support; and Dr. Robert Berghage for his knowledge on green roofs, plants and substrate.

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Chapter 1
Introduction

1.1 Statement of the Problem

Green roofs are a sustainable technology that could potentially offer several benefits to society and the environment. There have been several models proposing different ways to represent model green roof systems. Until now, none of these models have been properly verified and validated. Verification and validation is a key step of model development to prove that the model and user are correctly representing the physical phenomena and using the right mathematical models. Thus, there is a need for a model that properly models the important heat and mass transfer processes in a green roof.

1.2 Green Roof Characteristics

Green roofs are becoming popular in the U.S. with the green roof industry growing at a rate of 50% from 2001 to 2004 (Miller and Narejo 2005). Chicago is leading the way with about 32,000 m² of green roof installed in 2006, totaling more than 180,000 m² (Berkshir 2005, Johnston 2007). In addition, more than fifteen local governments in North America are in the process of establishing incentives to promote the installation of green roofs (Peck et al. 2005). For example, the City of Toronto has recently passed a new by-law consisting in a mandatory green roof installation in all types of new buildings in Toronto (Aster 2009). These incentives could be
connected to the beneficial performance of green roofs, such as reduction of thermal flux through the building roof.

Green roofs are defined as specialized roofing systems that support vegetation growth on human-made structures such as rooftops (Peck and Callaghan 1999, Liu et al. 2004). Green roofs are classified as extensive and intensive green roofs. Extensive green roofs when compared to intensive green roofs have lower weight, lower capital cost, minimal maintenance, and a substrate depth between 5 cm and 15 cm (Peck and Callaghan 1999, Snodgrass and Snodgrass 2006). Typical weight increase on the roof due to extensive green roof materials is from 72 kg/m² to 169 kg/m². In comparison, intensive green roofs have higher capital costs, wider planting selection, higher maintenance requirements, and increased substrate depth between 20 cm and 60 cm, which results in increased weight on the roof from 290 kg/m² to 968 kg/m² (Peck and Callaghan 1999). Thus, intensive green roofs are less cost-effective than extensive green roofs and required additional structural support (Peck and Callaghan 1999, Tanner and Scholz-Barth 2004). Moreover, extensive green roofs are the most common green roof, representing about 2/3 of the total green roof area installed in North America (Johnston 2007). Therefore, our modeling efforts focus on extensive green roofs as a more economically viable solution to be adopted in the building.

From top to bottom, a typical green roof consists of several layers: (1) vegetation, (2) growing medium, (3) filter membrane, (4) drainage layer, and (5) root resistance layer. Plants used on green roofs range from native plants and grasses to drought tolerant plants such as Sedum and Delosperma species, which belong to the cactus family of plants. Therefore, Sedum and Delosperma are hardy succulent plants, and have the ability to survive in drought conditions by limiting their water loss due to transpiration (Snodgrass and Snodgrass 2006). Substrate is a
lightweight porous soil-like layer that supports plant growth by retaining moisture and nutrients (Snodgrass and Snodgrass 2006). The substrate typically represents a mineral mix of sand, expanded clay, vermiculite, perlite, gravel, crushed brick, peat, organic matter and some soil (Peck and Callaghan 1999). The filter or cloth membrane prevents drainage clogging by containing the substrate and roots, and sometimes comes couple with the drainage layer. The drainage layer transports the rainfall runoff to the roof drain, and ventilates/aerates the substrate and consists of large size gravel, expanded clay, lava and pumice stone or plastic/polystyrene webbing or chambers, resembling an egg carton shape. Finally, the root resistance layer prevents root penetration into the roof membrane (Peck and Callaghan 1999, Peck 2002, Snodgrass and Snodgrass 2006).

The popularity of green roofs is increasing due to their potential benefits. In general, green roofs have a potential to (Liu and Baskaran 2004):

- reduce energy demand on space conditioning,
- reduce storm water runoff,
- expand the lifetime of roofing membranes,
- improve air quality,
- add aesthetic appeal, and
- reduce the urban heat island effect in cities.

The urban heat island effect is a phenomenon that explains warmer environmental temperatures in urban areas compared to those in surrounding rural areas during summer. Higher environmental temperatures have negative impacts on the society because of the increase in energy consumption, air pollution levels and heat related illness (EPA 2005). Therefore, green roofs can help address three of the four top problems facing the society in the next 50 years:
energy, water, and environment (Smalley 2005). In this way, the green roof technology has a potential to improve quality of population health and welfare in the urban areas with dramatically reduced vegetation.

1.3 Important Existing Findings

This thesis focuses on the fact that besides the reduced heat effects at the urban city scale, green roofs can make a difference for individual buildings and their thermal performance. This topic was previously explored, primarily in the form of case studies for individual buildings. An important part of the research done in North America focuses on the effects of the growing medium, and the plant selection in North American weather. Studies have compared: (1) performance of native plants versus Sedum type plants (Rowe et al. 2005), (2) effects of media depth in drought conditions (Thuring 2005), and (3) evapotranspiration rates (VanWoert et al. 2005, Rezaei, 2005, Berghage et al. 2007). These studies are important for the assessment of thermal performance of individual buildings because the depth and wetness of the growing medium significantly affect the heat transfer through the roof. Moreover, measured evapotranspiration rates could potentially be used to estimate the energy required to evaporate the water from plants and the growing medium. Evapotranspiration is also strongly related to the ability of green roof to reduce the urban heat island effect. Finally, evapotranspiration has an important role in runoff modeling of green roofs.
1.4. Research Objectives and Thesis Outline

The overall objective of this thesis is to develop a predictive heat and mass transfer model for green roof systems in summer conditions. The model is also verified and validated with experimental data from the “Cold Plate,” an experimental apparatus specifically designed and built to quantify heat and mass transfer processes.

Chapter two describes the fundamental physical phenomena taking place in a green roof. Chapter three analyzes the previous green roof models. Chapter 4 describes the new model. Chapter 5 describes previous experimental studies and chapter 6 describes the new experimental apparatus. Chapter 7 presents the experimental results and analyzes them. Finally chapter 8 contains the verification as well as the validation. The thesis last chapter has conclusions and future work.
Chapter 2

Heat and Mass Transfer on a Green Roof

This chapter introduces the most important concepts for the heat and mass transfer processes on a green roof. As discuss in this chapter, heat and mass transfer are connected through evapotranspiration process that influences both energy balance and water balance on a green roof.

2.1 Energy Balance for a Green Roof

The energy balance for a green roof can be generalized as follows (Jones 1992, Hillel 1998):

\[ R_n = ET + Q_{sensible} + Q_{conduction} + S_{thermal} + M \]  

Where,
\[ R_n = \text{net radiative flux, W/m}^2 \]
\[ ET = \text{evapotranspiration, or latent heat flux by convection, W/m}^2 \]
\[ Q_{sensible} = \text{sensible heat flux by convection, W/m}^2 \]
\[ Q_{conduction} = \text{conductive heat flux trough roof, W/m}^2 \]
\[ S_{thermal} = \text{thermal storage for substrate, plants, W/m}^2 \]
\[ M = \text{metabolic storage (photosynthesis and respiration), W/m}^2 \]

Equation (1) can be applied across the entire green roof (Gaffin et al. 2005) or by:
(a) separating plants, air around plants (canopy air), and the substrate
(b) separating plants and substrate (Best 1998, Herbs et al. 2008).
In Equation (1), thermal storage of plants is typically neglected by most green roof and soil-vegetation models, assuming quasi steady-state heat transfer. Also, the metabolic storage is often neglected because its contribution to the total energy sum is around 1-2% of the net radiation (Gates 1980, Jones 1992). However, this term can be as much as 5% of net radiation when there is a large mass of active vegetation in low light conditions (Hillel 1998), which would not typically be the case for an extensive green roof. An example of heat fluxes in Equation (1) are shown in Figure 2-1, which illustrates the ratio of each heat flux component divided by the incoming shortwave radiation in a laboratory experimental facility (Tabares-Velasco and Srebric 2009a).

![Figure 2-1 Ratio of heat fluxes in a green roof normalized with the incoming shortwave radiation as collected in a laboratory experimental test (Tabares-Velasco and Srebric 2009)](image)

Previous studies in urban (Tejeda-Martinez 1996), suburban (Barradas et al. 1999), and agricultural environments (Anderson et al. 1984) have measured similar ratios showing the importance of evaporation in Equation (1) to decrease substrate heat fluxes. Table 1 summarizes

<table>
<thead>
<tr>
<th>Component</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latent heat flux</td>
<td>0.82</td>
</tr>
<tr>
<td>Infrared radiation flux</td>
<td>0.24</td>
</tr>
<tr>
<td>Convective heat flux</td>
<td>0.16</td>
</tr>
<tr>
<td>Conductive heat flux</td>
<td>0.15</td>
</tr>
<tr>
<td>Reflected solar flux</td>
<td>0.11</td>
</tr>
<tr>
<td>Solar radiation flux</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Conductive heat flux trough green roof, 0.15

Table 1: Summary of heat flux components in a green roof.
the results from these different experimental studies (Barradas et al. 1999, Tejeda-Martinez 1996, Anderson et al. 1984). These data were collected over city blocks of Mexico City and an agricultural site in Nebraska. As shown in the table, even in dry suburban conditions, the ratio of evapotranspiration to the net radiation is still significant. The results shown in Table 1 for the suburban (wet) and agricultural areas are lower than results found in controlled laboratory experiments with plants, having ET/Rn equal to 0.85 (Gates 1980). Table 2-1 also shows that each heat transfer mechanism may have an important role in the heat flux reduction depending on the water content in the substrate. Finally, all of the heat transfer mechanisms in Equation (1) have multiple models used to simulate overall heat transfer in green roofs. As our present study focuses on the quasi steady-state conditions the heat transfer mechanisms to be modeled include: radiation, convection, evapotranspiration, and conduction.

Table 2-1: Energy flux ratios of sensible heat, soil conduction, and latent heat divided by the net radiation in suburban and agricultural areas

<table>
<thead>
<tr>
<th></th>
<th>Suburban Area (Dry)</th>
<th>Suburban Area (Wet)</th>
<th>Urban Area</th>
<th>Agricultural Area</th>
<th>Plant leaf in Laboratory (Gates 1980)</th>
<th>Green Roof Sample in Laboratory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{\text{sensible}}/R_n$</td>
<td>0.69</td>
<td>0.27</td>
<td>0.36</td>
<td>0.21</td>
<td>0.14</td>
<td>0.23</td>
</tr>
<tr>
<td>$Q_{\text{soil}}/R_n$</td>
<td>0.07</td>
<td>0.03</td>
<td>0.60</td>
<td>0.05</td>
<td>N/A</td>
<td>0.09</td>
</tr>
<tr>
<td>ET/R_n</td>
<td>0.25</td>
<td>0.70</td>
<td>0.04</td>
<td>0.72</td>
<td>0.86</td>
<td>0.68</td>
</tr>
</tbody>
</table>

2.2 Radiative Heat Transfer

Net radiation represents the difference between the incoming and outgoing radiation at the green roof surface. Net radiation consists of the short-wave or solar radiation (direct and diffuse) $R_{n,\text{solar}}$, and the long-wave or thermal infrared radiation from the surroundings $R_{n,\text{IR}}$, as following:
Net radiation for a leaf can be expressed as following (Jones 1992, Nobel 1983):

\[
R_n = \left( R_{n,solar} \right) + \left( R_{n,IR} \right)
\]  

(2)

Where,

\[ R_{n} = R_{sh} \left( I + \alpha_{soil} \right) \left( 1 - \alpha_{leaf} \right) + \left( \sigma T_{sky}^4 + \sigma \epsilon_{soil} T_{substrate}^4 - 2 \sigma \epsilon_{leaf} T_{leaf}^4 \right) \]  

(3)

The first term in the right hand side of Equation (3) represents the absorbed short-wave irradiance and the second term represents the thermal infrared radiative heat transfer between the leaf and the sky and the leaf and the top soil. However, representation of the radiation distribution on plant canopies is more complicated than a single leaf due to scattering and internal reflections of leaves and trapping of radiation. Previous green roof models that have conducted an energy balance on the roof calculated net radiation by using Beer’s Law and an extinction coefficients for long-wave and short-wave transmittances of a canopy as shown in Equation (4). Beer’s Law can be applied to total, diffuse or long-wave radiation, but different extinction coefficients should be used depending on the leaf configuration and type of radiation. Values for extinction coefficient for total transmitted radiation vary between 0.3 for vertical leaves to 1.5 for horizontal leaves (Ross 1975). Table 2-2 shows canopy transmittance values \( \tau_d \) for diffuse radiation for LAI values typical for a green roof. Table 2-3 shows extinction coefficients for ideal
and real plant configurations (Jones 1992, Monteith and Unsworth 2008). Table 2-2 and 2-3 show that horizontal and conical leaves have the largest extinction coefficients. Large extinction coefficients translate to larger shading (lower transmissivity) properties as compare to vertical leaves, a desire property for green roofs. Examples for horizontal and conical leaves could be *Sedum spurium* and *Delosperma nubigenum*, typical green roof plants.

\[
R_n = R_{sh} \left( I + \alpha_{soil} \right) \left( I - \alpha_{leaf} \right) \left( I - \tau_{solar} \right) + \left( \sigma T_{sky}^4 + \sigma E_{soil} T_{soil}^4 - 2 \sigma E_{leaf} T_{leaf}^4 \right) \left( I - \tau_{IR} \right) \quad (4)
\]

Where,

\[
\tau_{solar} = e^{-k_s LAI}, \text{ shortwave transmittance of a canopy}
\]

\[
k_s = \text{extinction coefficient}
\]

\[
\tau_{IR} = e^{-k_I LAI}, \text{ long-wave transmittance of a canopy}
\]

\[\text{LAI} = \text{leaf area index } \left( \frac{\text{leaf area}}{\text{soil surface}} \right)\]

**Table 2-2: Canopy transmittance values \( \tau_d \) for diffuse radiation (Ross 1975)**

<table>
<thead>
<tr>
<th>LAI</th>
<th>Horizontal</th>
<th>Vertical</th>
<th>Uniform</th>
<th>Maize</th>
<th>Cotton</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.368</td>
<td>0.504</td>
<td>0.443</td>
<td>0.429</td>
<td>0.404</td>
</tr>
<tr>
<td>2</td>
<td>0.135</td>
<td>0.314</td>
<td>0.219</td>
<td>0.201</td>
<td>0.173</td>
</tr>
<tr>
<td>3</td>
<td>0.050</td>
<td>0.213</td>
<td>0.113</td>
<td>0.098</td>
<td>0.075</td>
</tr>
</tbody>
</table>

**Table 2-3: Extinction coefficient values \( k_s \) for direct solar radiation (Jones 1992, Palomo del Barrio 1998, Monteith and Unsworth 2008)**

<table>
<thead>
<tr>
<th>Leaf Angle Distribution</th>
<th>Extinction Coefficient Equation for Direct Solar Radiation</th>
<th>Values</th>
<th>Direct Radiation</th>
<th>Longwave Radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Solar Elevation β = 90°</td>
<td>Solar Elevation β = 60°</td>
</tr>
<tr>
<td>Horizontal</td>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sunflower: 0.97</td>
<td></td>
</tr>
</tbody>
</table>

\[\text{Solar Elevation β = 60°} = 1-1.05\]
Definition of plant transmissivity shows that large LAI values are preferred to enhance plant coverage and plant shading. Definition of LAI varies depending on field of study or approach taken (Scurlock et al. 2001). The most common definition of LAI is the projected or shadow leaf area divided by the ground area. However, other studies recommend the use of half of the total intercepted leaf area divided by the ground area as a more robust definition for all types of leaves (Chen and Black 1992).

Radiative heat exchange from the substrate has been often neglected or simplified. A couple of green roof models have treated green roofs as a whole element when calculating an energy balance. Thus, these models do not include the radiative heat transfer between the substrate-plants, and substrate-sky (Nayak et al. 1982, Cappelli et al. 1998, Lazzarin et al. 2005, Gaffin et al. 2005, Gaffin et al. 2006). Finally, all the radiation sub-components of the models need the spectral properties of plants and most also need a proper extinction coefficient.

Overall, for most leaves, the total solar absorptance is from 0.4 to 0.6, typically used as 0.5 in calculations (Nobel 1983) having a solar transmissivity of 0.20 and a solar reflectivity around 0.30 (Ross 1975). However, for desert succulent plants the solar absorptance is from 0.59

<table>
<thead>
<tr>
<th>Shape</th>
<th>Formula</th>
<th>α = 90°</th>
<th>β = 0.50</th>
<th>N/A</th>
<th>0.43-0.29</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylindrical</td>
<td>( \frac{2}{\pi \cdot \tan(\beta)} )</td>
<td>0.00</td>
<td>0.37</td>
<td></td>
<td>0.436</td>
</tr>
<tr>
<td>Spherical</td>
<td>( \frac{1}{2 \cdot \sin(\beta)} )</td>
<td>0.50</td>
<td>0.58</td>
<td>N/A</td>
<td>0.684-0.81</td>
</tr>
<tr>
<td>Conical</td>
<td>( \frac{\cos(\alpha)}{2 \cdot \cos(\alpha)} )</td>
<td>0.50</td>
<td>0.50</td>
<td>N/A</td>
<td>0.829</td>
</tr>
</tbody>
</table>

*Note: Cone wall angle

*Cones with wall angle α*

\( \beta > \alpha * \)
to 0.83, having a transmittance of zero (Gates et al. 1965). Moreover, vegetated canopies tend to have lower reflectivity, from 0.15-0.24, due to multiple reflections and radiation trapping (Jones 1992, Monteith and Unsworth 2008). For example, short grass can have an albedo of 0.26, while one meter long grass has an albedo of 0.16 (Pielke 2002).

Emissivity for leaves is usually 0.96, but it can be as low as 0.92 and as high as 0.98 (Gates 1980, Nobel 1983). For example, grass emissivity ranges from 0.90-0.97 (Pielke 2002) while cactus emissivity is 0.98 (Monteith and Unsworth 2008).

Due to the ranges in these values, the reflectivities for wet and dry green roof samples with *Sedum spurium* were measured using a spectroradiometer. Spectral reflectance of the green roof canopy sample is presented in Figure 2-2. The data agrees well with published spectral reflectivities (Gates 1980). Overall, the plants absorbed most of the radiation in the UV, visible and Photosynthetically Active Region (PAR) part of the spectrum. PAR is the range of the spectral power distribution of the sun that plants can use in photosynthesis. PAR wavelength ranges from 400nm to 700 nm. According to the literature, leaf absorption of radiation in PAR is the highest with typical absorptance values from 0.75 to 0.90 (Nobel, 1983) or reflectivities of 0.05 for PAR (Jones 1992). These values are very similar to the values in Figure 2-2, having an average reflectivity of 0.03. In contrast, absorption of radiation is the lowest in the near-infrared region from 700 nm to 1200 nm. Reflectivities for desert plants in the near-infrared region values vary from 0.20 to 0.50 (Gates 1980). Desert plants are succulent plants as well as sedum-like plants used in extensive green roofs. Similarly, our data represented in Figure 2-2, shows an average reflectivity of 0.28 for the same region. Overall, total measured solar reflectivity for a green roof sample is around 0.06, a value below the reported for grass or other plants. The difference between the measured reflectivity and the value from literature is mainly due to plant
specific properties and approach used. Most of reported reflectivity’s values on the literature are for leaves, the value measured here combines the reflectivity of a vegetated canopy and underlying substrate.

![Spectral Reflectivity of Green Roof Sample](image)

**Figure 2-2**: Spectral reflectivity of a green roof sample mainly covered by *Sedum spurium*.

Soils reflectivity varies according to soil type and water content varying from 0.10 for wet soil to 0.35 for dry soil. In contrast, soil emissivity is not as dependant to water content, and typical values for soil emissivity are 0.90-0.98 (Pielke 1992). Figure 2-3 shows different albedo values measured for different soils and green roof substrates (Pielke 1992, Sailor et al. 2008).
2.3 Convective Heat Transfer

Convective or sensible heat transfer accounts for the heat that is transported to the air above the plant canopy or substrate, thus heating/cooling the air by means of convection. Depending on the field of study, convective heat transfer is calculated as either a resistance (conductance) or an overall heat transfer coefficient. The following equation defines the convective heat transfer for a green roof:

\[ Q_{\text{sensible}} = \rho C_p \frac{r_a}{r_{a,\text{heat}}} (T_{s,o} - T_{\text{air}}) = \rho C_p h_{\text{heat}} (T_{s,o} - T_{\text{air}}) = h_{\text{convection}} (T_{s,o} - T_{\text{air}}) \]  (5)

Where,
\[ r_a = \text{aerodynamic resistance, s/m} \]
\[ h_{\text{convection}} = \text{convective heat transfer coefficient, W/m}^2\text{C} \]
\[ h_{\text{heat}} = \text{heat transfer conductance, m/s} \]

The boundary layer resistance can be simply estimated assuming leaves are isothermal and are in the form of flat plates, cylinders, or spheres with laminar forced convection (Gates...
1980, Jones 1992). However, turbulence is likely to occur, especially on a roof. Using laminar
models could underestimate the resistance by a factor of 1 to 3 (Jones 1992).

Another approach to calculate the aerodynamic resistance, commonly used in
meteorology and mesoscale analyses, follows the law of the wall, or logarithmic wind profile.
Some green roof models have used this logarithmic profile for plant communities combined with
stability functions to account for buoyancy effects (Zhang et al. 1997, Sailor 2008). For neutral
atmospheric stability or in a forced convection regime, aerodynamic resistance to heat exchange
can be calculated using the following equation (Jensen 1990, Allen et al. 1998):

\[
\frac{r_d}{k^2u} = \ln\left(\frac{z_m - d}{Z_{om}}\right) \ln\left(\frac{z_h - d}{Z_{oh}}\right)
\]

Where,
- \(z_m\) = height of wind measurements, m
- \(z_h\) = height of humidity and temperature measurements, m
- \(d\) = zero plane displacement height, m
- \(Z_{om}\) = roughness length governing momentum transfer, m
- \(Z_{oh}\) = roughness length governing transfer of heat and vapor, m
- \(k\) = von Karman's constant, 0.41
- \(u_z\) = wind speed at height \(z\), m/s

Equation (6) can be simplified for crops assuming \(d = 2/3\) \(h\), \(Z_{om} = 0.123\) \(h\), \(Z_{oh} = 0.1Z_{om}\),
and a wind and humidity heights equal to two meters. In these approximations, \(h\) is the plant
height. For \( h = 0.10 \) m, the simplified version of the boundary layer resistance is (Allen et al. 1998):

\[
\frac{r_u}{u} = \frac{208}{u}
\]  

(7)

Thus, the equivalent convective heat transfer coefficient for Equation (7) is:

\[
h_{ru} = 5.6u \frac{W}{m^2 K}
\]

(8)

Equation (6) has the advantage because it does not require a characteristic length, which is required for the Nusselt-Reynolds correlation. However, this approach assumes the surface is uniform, extensive, and horizontal, and turbulence is generated by shear stress at the surface and not by upwind obstructions (Monteith and Unsworth 2008), which may not be the case on a green roof. In contrast, the empirical equations for a flat plate with forced turbulent and laminar convective heat transfer are not linear. These equations can be expressed here in terms of the wind speed and characteristic length, \( L \) (Incropera 2002):

\[
h_{turb} = 5.82 \times L^{0.2} \times u^{4/5} \frac{W}{m^2 K}
\]

(9)

\[
h_{lam} = 3.84 \times L^{0.5} \times u^{1/2} \frac{W}{m^2 K}
\]

(10)

Heat transfer for leaf or group of leaves can be calculated using Equation (10) with the addition of multiplier, \( \beta_{conv} \), which ranges from 1.4 to 2.5 for forced convection (Schuepp 1993). Moreover, same studies have recommended lowering the critical Reynolds number to 20,000 (Schuepp 1993). A green roof model uses a similar formula as Equation (9) (Gaffin et al. 2005) for wind speed higher than 1.75 m/s. Older green roof models have used a linear relationship with
wind speed to calculate convective heat transfer coefficient (Nayak et al. 1982, Cappelli et al. 1998). However, a recent study compared the use of a linear relationship against the wind log profile to calculate convection (Alexandri and Jones 2008). The wind log profile had better agreement with experimental data. In addition, the largest difference in both equations compared to experimental data was during the hottest time of the day. This could be an indication that models need to incorporate mixing convection in their convective transport phenomena or a redefined characteristic length.

2.4 Latent Heat Transfer or Evapotranspiration

Latent heat transfer in green roofs is a combined process of water lost from the soil evaporation and plant transpiration, also called evapotranspiration. Transpiration occurs when water from the plant leaf surface is transported into the air by diffusion and/or convection. Most of the water losses in plants are through plant stomata. Stomata are adjustable small pores in the leaf that allow the entry of gases needed for photosynthesis such as CO₂, and the release of O₂ and water vapor. Thus, this is a natural control mechanism that allows plants to control their transpiration rate by opening and closing their stomata (Nobel 1983, Allen et al. 1998, Hillel 1998).

Evaporation of liquid water into water vapor requires energy, which in this case comes primarily from the sun, and from the ability of the ambient air to absorb water vapor. The driving force for evapotranspiration is the Vapor Pressure Deficit (VPD). The vapor pressure in the surrounding air must be lower than the internal plant vapor pressure for evapotranspiration to occur. The water vapor then is transported to the air by means of convection. Thus, the parameters affecting evapotranspiration are environmental variables such as solar radiation, air
temperature, air humidity, and wind speed, but there are also other factors related to plant type and substrate/soil water content (Allen et al. 1998, Hillel 1998).

The method to calculate evaporation from a wet saturated surface was developed by Dalton in 1802. Equation (11) is based on the vapor pressure difference between the evaporative surface and the surrounding air (Gates 1980).

\[ E = (e_s - e_{\text{air}})f(u) \]  

Where,

- \( e_s \) = vapor pressure at the evaporative surface, kPa
- \( e_{\text{air}} \) = vapor pressure of the air, kPa
- \( f(u) \) = function of the wind speed, W/m\(^2\)·kPa

\[ f(u) = 74.4(1 + 0.53u), \text{W/m}^2/\text{kPa} \] (Jensen et al. 1990)

The function of the wind speed is an empirical equation formulated by Penman in 1948, and subsequently modified by several researchers the upcoming years and decades for different field conditions and crop types. Thus, several linear relationships exist depending on the geographic locations and crop type (Jensen et al. 1990). However, these functions are linear regressions that do not represent the variability of day and night, canopy properties, and meteorological conditions (Rana and Katerji 2000). For those reasons, Monteith introduced an aerodynamic and surface resistance to heat and mass (vapor) transfer that is now widely used for evapotranspiration calculation (Hillel 1998).

\[ ET = \frac{\rho C_p}{\gamma(r_s + r_a)}(e_{s_o} - e_{\text{air}}) \]  

Where,
eso = vapor pressure of the air in contact with the surface, kPa

rs = stomatal resistance to mass transfer, s/m

ra = aerodynamic resistance to mass transfer, s/m

γ = psychrometric constant = $C_p P / 0.622 i_{fg}$, kPa/°C

ifg = enthalpy of vaporization, kJ/kg

P = atmospheric pressure, kPa

When the substrate/soil is completely covered by plants, one can assume that equation (12) combines all resistances to mass and heat transfer of the soil, internal plant resistances (stomata, cuticular) and soil and leaves boundary layer into two main resistance in series: bulk surface resistance and the aerodynamic resistance (Allen et al. 1998). Thus, the resistance to vapor transfer is the sum of the boundary layer (aerodynamic) resistance, ra, and the bulk canopy resistance, rc (Hillel 1998). When the plants are not completely covering the substrate, a resistance factor should be included to accounts for soil evaporation.

Equation (12) requires knowledge of vapor pressure of the air in contact with the surface and/or surface temperature, data somehow difficult to obtain and measure. Observing these limitations, Penman developed a new equation by using Equation (11) and making an energy balance around the evaporating surface (Jensen et al. 1990). Monteith later modified this equation by incorporating the aerodynamic and surface resistance to heat and mass showed in Equation (12). This now widely validated model in crops is the known as the Penman-Monteith model:

$$ ET = \frac{\Delta(R_n - Q_{soil}) + \rho C_p (e_{PM} - e_a)}{\Delta + \gamma \left( I + \frac{r_s}{r_a} \right)} $$

Where,

$$ e_{so} $$

$$ r_s $$

$$ r_a $$

$$ \gamma $$

$$ i_{fg} $$

$$ P $$

$$ \rho $$

$$ C_p $$

$$ e_{PM} $$

$$ e_a $$

$$ \Delta $$

$$ \gamma $$

$$ I $$

$$ r_s $$

$$ r_a $$

$$ \rho $$

$$ C_p $$

$$ e_{PM} $$

$$ e_a $$

$$ \Delta $$

$$ \gamma $$

$$ I $$

$$ r_s $$

$$ r_a $$

$$ \rho $$

$$ C_p $$

$$ e_{PM} $$

$$ e_a $$

$$ \Delta $$

$$ \gamma $$

$$ I $$

$$ r_s $$

$$ r_a $$

$$ \rho $$

$$ C_p $$

$$ e_{PM} $$

$$ e_a $$

$$ \Delta $$

$$ \gamma $$

$$ I $$

$$ r_s $$

$$ r_a $$

$$ \rho $$

$$ C_p $$

$$ e_{PM} $$

$$ e_a $$

$$ \Delta $$

$$ \gamma $$

$$ I $$

$$ r_s $$

$$ r_a $$

$$ \rho $$

$$ C_p $$

$$ e_{PM} $$

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$$ \rho $$

$$ C_p $$

$$ e_{PM} $$

$$ e_a $$

$$ \Delta $$

$$ \gamma $$

$$ I $$

$$ r_s $$

$$ r_a $$

$$ \rho $$

$$ C_p $$

$$ e_{PM} $$

$$ e_a $$

$$ \Delta $$

$$ \gamma $$
\( e_{s,PM} \) = vapor pressure of the air, kPa

\( \Delta = \) slope of the saturation vapour pressure, \( \Delta = \frac{4098e}{(T + 237.3)^2} \), kPa/°C

The Penman-Monteith model assumes the canopy is a single “big leaf” having average physiological properties. Equation (13) is based on (12) after several mathematical substitutions and assumptions described in the literature (Thom 1975). As a result Equation (13) does not require the use of leaves surface temperature to calculate the vapor pressure differential. Thus, data is only needed at one height above the surface, rather than two or more data measurements at different elevations (Brusaert 1982). This model is also recommended by the Food and Agriculture Organization (FAO) of the United Nations that calculates evapotranspiration for a hypothetical well watered grass surface. Using the FAO assumption requires the addition of a crop coefficient to allow conversion to other plant evapotranspiration rates as well as another coefficient for water stress conditions. This assumption of plant type and water regime limits the use of the hypothetical case for a green roof scenario. An older version of Penman-Monteith model based on the original Penman model was used by another green roof model (Lazzarin et al. 2005).

Another way to measure and calculate evapotranspiration is by the Bowen ratio. Bowen ratio is the ratio of transport of the sensible heat and the latent heat, presented as following (Hillel 1998):

\[
\beta = \frac{Q_{sensible}}{ET} \approx \gamma \frac{\Delta e}{\Delta T}
\]  

(14)

The Bowen ratio basically depends on the interaction between heat and mass transport phenomena (Hillel 1998) and once the value is known, evapotranspiration can be calculated as following:
\[ ET = \frac{Q_{\text{sensible}}}{\beta} = \frac{h_{\text{convection}}(\Delta T)}{\beta} \] (15)

For an irrigated field, \( \beta \) is about 0.2. However, this value changes depending on the water availability and weather conditions (Hillel 1998). In suburban areas, values for \( \beta \) found in the literature are from 0.04 to 1.92 (Barradas et al. 1999). Calculated values for green roofs are between 0.12 and 0.35 (Gaffin et al. 2006). Another study includes a coefficient that allows for Bowen ratio changes depending on the water content in the soil (Jacobs et al. 1997).

Most of the complex green roof models have followed the vapor pressure deficit (VPD) approach, using Equation (12). Two of these models use the linear wind correlations together with VDP (Nayak, et al. 1982, Lazarin et al. 2005). The other four models use VPD and the concept of aerodynamic and canopy resistances (Zhang et al. 1997, Palomo Del Barrio 1998, Alexandri and Jones 2007, Sailor 2008). Only one model used empirical Bowen ratios (Gaffin et al. 2006) or an evaporative efficiency (Takebayashi and Moriyama 2007). For those models using aerodynamic and canopy resistance, most of their differences are in the resistance models, assumptions, and inclusion of LAI into Equation (12).

In conclusion, there are two main methodologies to calculate ET: VPD and Bowen ratio. VPD approach represents the Dalton-type equation such as Equation (12) and the Penman-Monteith equation. Both need either an empirical wind equation or a surface and aerodynamic resistances. However, empirical wind equations may not be applicable to a green roof. Thus, the surface and aerodynamic resistances will be used in this thesis. Conversely, the Penman-Monteith equation requires information about surface temperature, as net radiation and conductive heat flux are required. All VPD methods based on stomatal resistance require calculation of plant internal resistance mainly due to stomata, and calculation of convective resistance to mass and heat
transfer. Analogous to heat transfer, a resistance to heat transfer is used. An analogous version of Equation (6) is available, based on the similarity hypothesis (Thom 1975). Based on the analysis done in this Chapter, both VPD methodologies will be analyzed for their used in the new green roof model.

### 2.4.1 Stomatal Resistance

The plant internal resistance is the resistance to vapor flux through the leaf surface. This resistance depends mainly on the stomatal resistance (Jones 1992), which is a function of the LAI, solar radiation, temperature, and water availability (Hillel 1998).

An available equation to determine canopy resistance of a fully-vegetated roof area is (Allen et al. 1998):

$$ r_s = \frac{r_i}{0.5 \text{LAI}} \tag{16} $$

where,

- $r_i =$ stomatal resistance of the well-illuminated leaf, s/m,

The 0.5 multiplier suggests that only half of the canopy is effectively transpiring (Allen et al. 2006). Equation (16) assumes the stomata layer at the leaf surface is the only layer that significantly participates in the transpiration (Rana and Katerji 2000). The stomatal resistance depends on weather and water availability, and tends to increase as the water content in the soil decreases (Allen et al. 1998). For clipped grass less than 0.15 m high, LAI is $24 \times h$, where $h$ is
the grass height (Allen et al. 1998). For non-clipped grass and alfalfa taller than 0.03 m, LAI is calculated with the following equation: \( \text{LAI} = 1.5 \ln(h \times 100) - 1.4 \) (Jensen et al. 1990).

Minimum values for stomatal resistances vary from 450-1000 s/m for succulent plants to 225-1125 s/m for desert plants (Jones 1992). For well-watered grass, the canopy resistance is 70 s/m (Allen et al. 1998). From all the different groups of plants with measured data available in the literature, succulent and desert plants have the highest leaf resistance (Jones 1992). In a green roof study, stomatal resistance measured for grass was found to be 250-600 s/m (Alexandri and Jones 2007).

Studies focused mainly on crops have proposed multiple regressions with variable resistances to increase model accuracy. The leaf resistance is calculated with various independent variables, such as air temperature, humidity, solar radiation, and wind speed (Gates 1980, Jones 1992, Zhang et al. 1997, Todorovic 1999, Alexandri and Jones 2007). For hourly calculation, using a variable stomatal resistance should be considered, at least in semiarid and windy conditions (Lecina et al. 2003). However, other results showed good agreement in well-watered fields using constant stomatal resistance (Todorovic 1999, Allen et al. 2006), as the plants were not under water stress conditions.

For green roofs, a previous study proposed the following variable canopy resistance by Soil-Vegetation-Atmosphere-Transfer models (Deordorff 1978), which had a good agreement with measured stomatal resistance (Alexandri and Jones 2007):

\[
\eta_s = \eta_{\text{root}} + \left( \frac{I_{\text{solar}, \text{max}}}{0.03I_{\text{solar}, \text{max}} + I_{\text{solar}}} + \frac{P_{\text{grow}} + \left( \frac{\eta_{\text{wilt}}}{\eta_{\text{root}}} \right)^2}{0.5 \text{LAI}} \right)
\]

(17)
However, according to the literature, the most complete method should use a multiplicative resistance model rather than an additive model (Jones 1992, Rana Katerji 2000). This is the approach based on most current mesoscale models (Pielke 2002) and was originally proposed more than three decades ago (Jarvis 1976). Two green roof models use this approach; each one defined different multiplicative functions and coefficients (Del Barrio 1998, Sailor 2008) with a generalized format as follows:

\[
rs = \frac{r_i}{0.5 \times LAI} \times f(\text{solar}) \times f(\text{water}) \times f(VPD) \times f(\text{temperature}) \times f(CO_2) \quad (18)
\]

However, there are several different empirical multiplicative functions. For example, Figure 2-4 to Figure 2-6 show the effect that different functions developed from independent studies simulating the role variables, such as (1) solar irradiance, (2) VPD, and (3) substrate water content, have on stomatal aperture. From all functions shown in Figure 2-4, functions 1 and 3 predict a stomatal aperture to be approximately 40% open, while others predict almost 100% open aperture when irradiance is 100 W/m². The same problem is present when comparing the effect that different empirical functions modeling the role of vapor pressure differential (Figure 2-5) and substrate water content (Figure 2-6) have on stomatal aperture.
Solar Radiation Role on Stomatal Behavior

Data used in Figure 2-4 came from:

- Model 1: Function developed for land surface or soil-vegetation-atmosphere schemes (van de Hurk et al. 2000). Function used in a green roof model (Sailor 2008).
- Model 2: Function developed for land surface or soil-vegetation-atmosphere schemes (Dickinson 1984). Maximal stomatal resistance was set equal to 5000 s/m and a coefficient of 100 W/m², for crops, was used. Function used by a SVAT model (Jacquemin and Noilhan 1998)
- Model 3: Function developed from conductance resistance measurements of tropical forest (Dolman et al. 1991). Function used by a SVAT model (Best 1998)
- Model 4: Function used in LAPS scheme (Pielke 2002). Maximal stomatal resistance was set equal to 5000 s/m and LAI equal to 2.
- Model 6: Function developed from tomato plants (Stahghellini 1987). Function used in green roof model (Palomo del Barrio 1998).
- Model 7: Function developed over a forest area (Stewart 1988).
- Model 8: Function recommended from studies over forest area (Deordoff 1978).
Figure 2-5: Empirical multiplicative functions for VPD role on stomatal aperture.

Data used in Figure 2-5 came from:

- Model 1: Exponential function developed from tobacco plant experimental research (Avissar and Pielke 1991).
- Model 2: Linear function developed from diffusion porometer on *Sitka spruce* (pine) (Jarvis 1976).
- Model 3: Linear function developed from chamber studies on *Douglas fir* (pine) (Jarvis 1976).
- Model 4: Logarithmic function developed from conductance measurement on *Larrea tridentate* (desert shrub) (Ogle and Reynolds 2002).
- Model 5: Logarithmic function developed from sap flow measurement *Larrea tridentate* and *Ephedra nevadensis* (desert shrub) (Oren et al. 1999).
- Model 6: Logarithmic function developed from sap flow measurement *Pinus flexilis* and *Pinus contorta* (Pine) (Oren et al. 1999).

As shown in Figure 2-5, there two main types of mathematical functions that simulate stomatal aperture based on VPD: linear and logarithmic functions (Jones 1992). All $f_{VPD}^{-1}$
functions shown in Figure 2-5 have values equal to 1 when the air is saturated (VPD equal to 0). However, previous linear functions tend to yield negative values for large VPD values commonly found on desert environments. Other mesoscale (van de Hurk et al. 2000) and green roof models (Sailor 2008) have concluded that VPD only has a significant role on stomatal aperture in large trees; however, there are at least couple of studies that have extensively concluded the opposite (Oren et al. 1999, Ogle and Reynolds 2002). These last two studies have developed logarithmic equations for plants from different climates, including desert shrubs. Thus, a logarithmic equation with coefficient developed from desert plants are used in this study.

Finally, the last function evaluated here is based on substrate volumetric water content. Some mesoscale models (Avissar and Pielke 1991) have used soil moisture potential instead of volumetric water content. Soil moisture potential is the potential energy to extract water against soil capillary and sorption forces (Jacobson 2005). However, experimental data also included in Figure 2-6 showed that stomatal aperture depends on water content.

![Substrate Water Content Role on Stomatal Behavior](image)

Figure 2-6: Empirical multiplicative functions for Substrate Volumetric Water Content (VWC) role on stomatal aperture.
Data used in Figure 2-6 came from:

- Data 1: Experimental data from conductance of *Nerium oleander* (evergreen shrub) (Gollan et al 1985).
- Data 2: Experimental data from conductance of *Triticum aestivum* (wheat) and *Helianthus annuus* (sunflower) (Gollan et al 1986).
- Model 1: Empirical power function equation used by LAPS (Pielke).
- Model 2: Linear function developed from transpiration calculations for crops and trees (Jacquemin and Noilhan 1988). It depends on substrate water content and field conditions $VWC_{fc}$.
- Model 3: Quadratic function developed using same information as model 2. (Ronda et al. 2001)
- Model 4: Linear function developed from transpiration calculations for crops and trees. Model similar to model 3 using $VWC_{fc}$ instead of $0.75 \cdot VWC_{sat}$. (Noilhan and Planton 1990)
- Model 5: Same linear function as in model 2, but using $0.75 \cdot VWC_{fc}$ instead of $0.75 \cdot VWC_{sat}$.
- Model 6: Same quadratic function used in model 3, but using $0.75 \cdot VWC_{fc}$ instead of $0.75 \cdot VWC_{sat}$.

All models shown in Figure 2-6 depend on volumetric water content and volumetric water content at saturation, field capacity, and/or wilting point. The volumetric water content values used for these three conditions are: (1) 0.55 for fully saturated (Denardo 2003), (2) 0.34 for field capacity (Denardo 2003), and (3) 0.02 for wilting point (Berghage R., pers. comm., September 9, 2008). Wilting point is the volumetric water content when plant roots can no longer extract more water from the substrate (Monteith and Unsworth 2008). Field capacity is the state after all excess water in the substrate has already been drained by gravity (Monteith and Unsworth 2008). Function 5 shows better performance than the other functions. However, all functions will be assessed in this thesis.
The decision on whether to use one function or another should be based on comparing model output with experimental data, as many of these functions were developed from data for pines or rainforests, which are ecosystems that do not necessarily resemble green roofs. This validation task has not been performed for green roofs. Therefore, to the best of our knowledge, this thesis is the first research project to validate a green roof model using latent heat flux and heat flux through the roof.

2.4.2 Bare Soil Latent heat flux

Bare soil evaporation may also play an important role when the plants are establishing, or, in the worse case scenario, when all plants die. If the soil is not completely covered by plants, the resistance should include the resistance of the exposed soil. For a soil completely covered by vegetation, the ratio of evaporation from soil to total evaporation is around 0.10 (Gates, 1980), but this value depends on LAI (Jacobs et al. 1997). For example, with LAI values between 0.3 and 0.5, the ratio of wet soil evaporation to total evaporation can be as high as 0.50 to 0.80 (Wallace et al 1993).

Previous research described soil evaporation as a soil-drying process in three stages (Hillel 1998):

1. Initial, constant-rate stage - Soil is wet and water evaporation depends mainly on environmental parameters, such as wind and air vapor pressure (potential rate). This stage lasts from a few hours to a few days.
2. Intermediate, falling-rate stage - Evaporation decreases below the potential rate and is limited by the substrate water content. This stage lasts longer than the first stage.
3. Residual, slow-rate stage - Evaporation is minimal, as water movement to the topsoil is mainly due to vapor diffusion and is affected by adsorptive forces of the substrate. This stage may last weeks or months.

As the soil surface dries, evaporation takes place at lower levels, and thus the resistance to water vapor increases. Approaches to quantify soil evaporation vary from nonlinear equations that calculated cumulative evaporation depending on time (Hillel 1998) to coefficients added to the potential evaporation (Ye and Pielke 1993). The efforts done with the latter approach can be explained with the following three equations (Mahfouf and Noihlan 1991, Ye and Pielke 1993):

\[
ET = \frac{\rho \cdot C_p}{\gamma(r_a)} \left( \alpha \times e_{so} - e_{air} \right)
\]

(19)

\[
ET = \frac{\rho \cdot C_p}{\gamma(r_a)} \left( \beta \left( e_{so} - e_{air} \right) \right) = \frac{\rho \cdot C_p}{\gamma(r_a + r_{soil})} \left( e_{so} - e_{air} \right)
\]

(20)

\[
ET = \frac{\rho \cdot C_p}{\gamma(r_a)} \left( \beta \left( \alpha \times e_{so} - e_{air} \right) \right) = \frac{\rho \cdot C_p}{\gamma(r_a + r_{soil})} \left( \alpha \times e_{so} - e_{air} \right)
\]

(21)

where,

- \( e_{so} \) = saturated vapor pressure at the soil temperature, kPa
- \( \alpha \) = relative humidity of air at the land surface
- \( \beta \text{soil} \) = moisture availability parameter = \( r_a \) \\
  \( r_{soil} \)
- \( r_{soil} \) = soil surface resistance to mass transfer, s/m

Models to calculate \( \alpha \), \( \beta \text{soil} \), and \( r_{soil} \) are compared in the literature (Mahfouf and Noihlan 1991, Ye and Pielke 1993). The cumulative dependent model calculated much higher evaporation rates compared to the one calculated by the \( \alpha \) and \( \beta \text{soil} \) methods (Mahfouf and Noihlan 1991). In
contrast, the $\alpha$ and $\beta_{\text{soil}}$ methods also need further work, as these methods need either calibration or specific treatment of dew (Mahfouf and Noihlan 1991). However, one of the methods that had the best performance was a combination of both methods shown in Equation (21) (Mahfouf and Noihlan 1991). As with plant stomatal resistance, Figure 2-7 displays seven different $r_{\text{soil}}$ empirical models developed for different soils. The difference between models are because each of the models’ results are based on measured average volumetric water content at different layers, such as the top 0.5 cm, 1 cm, 2 cm, or 5 cm.

![Substrate Resistance to Water Vapor Diffusion](image)

**Figure 2-7:** Soil surface resistance models to vapor transfer.

Data used in Figure 2-7 came from:

- **Model 1:** Power function based on volumetric water content from upper 0.5 cm layer (Sun 1982).
- **Model 2:** Exponential function based on volumetric water content from upper 1 cm layer (van de Griend and Owe 1994).
- **Model 3:** Empirical exponential function (Passerat 1986). No information available on soil layer used for volumetric water content.
• Model 4: Linear function based on volumetric water content from upper 0.5 cm layer (Camillo and Gurney 1986).
• Model 5: Power function based on volumetric water content from upper 2 cm layer (Kondo et al. 1990).
• Model 6: Power function based on volumetric water content from upper 5 cm layer (Olioso et al. 1999).
• Model 7: Power function based on volumetric water content from upper 5 cm layer (Bussiere 1985).

Model number 1 (Sun 1982) has been accidentally modified (Dolman 1993) by probably a typo mistake. Thus subsequent publications (Bastiaanssen 1995, Acs 2003) has included the so-called Dolman model, while careful investigation of the original publication shows that is clearly a typo mistake (Dolman 1993).

2.5 Heat flux through green roof substrate

Soil and substrate thermal conductivity depends on several factors such as: conductivity of individual soil particles, density, water content, organic, mineral, and quartz content (Farouki 1986, Pielke 2002). The two most common methods to calculate the soil conductivity are the Johansen and the De Vries methods (Farouki 1986). Inputs for the first method include density, porosity, degree of saturation, quartz content, and thermal conductivity of the contained minerals. The De Vries method requires the porosity, soil solids thermal conductivity, and organic content for the conductivity calculations (Farouki 1986).

However, green roof substrate is different from regular soil. Substrate is made up of lightweight granular solids, has lower density, has different organic content, and does not fit into
soil definition because of the larger granular size. For example, typical conductivities for soil vary from 0.2 to 2 W/m K for dry and wet soil respectively (Nobel 1980). Thermal conductivity for typical dry green roof substrate is between 0.18 and 0.22 W/m K. For saturated substrate, thermal conductivity ranges from 0.5 to 1.0 W/m K as shown in Figure 2-8.

![Substrate Thermal Conductivity](image)

**Figure 2-8**: Thermal conductivity for several green roof substrates.

Data used in Figure 2-8 came from:
- Data Mulch: Experimental correlation based on data for a mixture of pine bark with 10% compost (Saiz Alcazar 2005).
- Data GR: Linear correlation from laboratory samples for eight different mixtures consisting of expanded shale, pumice, compost, and sand. The density of the substrates ranged from 770 kg/m³ to 1360 kg/m³ (Sailor et al. 2008).
• Model GR 1: Linear correlation for media consisting of volcanic rock, pumice, and expanded clay. The density of the substrate equal to 600 kg/m³ (Perino et al. 2003a).

• Model GR 2: Linear correlation from on-site experimental research, no information for substrate properties were found in the literature (Takebayasi and Moriyama 2007).

• Soil Model 1: Johansen’s correlation for a crushed rock with the solid conductivity of 1.5 W/m K, porosity of 0.70, quartz content of 0.15, and substrate density equal to 800 kg/m³ (Farouki 1986).

• Soil Model 2: De Vries’ correlation for a soil with the solid conductivity of 1.5 W/m K, porosity equal to 0.70 (Farouki 1986).

• Soil Model 3: Kersten’s model for a soil with density equal to 800 kg/m³ (Farouki 1986).

• Soil Model 4: Experimental correlation based on a large sample of soils with densities from 1100 kg/m³ to 1500 kg/m³ and VWC from 4 to 25% (Palomo Del Barrio 1998).

As shown in Figure 2-6, the two most recommended soil models developed for regular soils, De Vries and Johansen models, overestimate the green roof experimental data. A reason for this disagreement could be the lack of information on the quartz content. However, these models could simply not be able to represent the conductivity of green roof substrate because typical green roof substrates, such as expanded clay, contain aggregates with interior air pockets. The differences for the rest of the empirical correlations are within the accuracy of the used sensors/methodology, calculated based on the information provided by the research study, or by the known uncertainties of the apparatus used in each project. It is also important to mention that the studies used different methods to calculate the conductivity: steady-state method (Perino et al.
2003, Saiz Alcazar 2005, Takebayasi and Moriyama 2007, Tabares-Velasco and Srebric 2009a) or transient method (Sailor et al., 2008). Overall, these data/equations will be used to develop a general substrate thermal conductivity equation

2.6 Conclusions

Heat balance across a green roof shows that the three heat transfer mechanism occur along a green roof plus latent heat flux. Previous studies have quantified these different transport processes and identified that latent heat flux have an important role when the green roof is wet. Moreover, due to the interdependency of all transport processes, it is important to model all these four phenomena correctly. The next chapter will describe how previous green roof models have modeled heat and mass transfer processes in a green roof.
Chapter 3

Theoretical Models

This chapter introduces previous studies with the main goal to model green roofs. These models will be classified and analyzed depending on their characteristics and assumptions. For example, models will be compared on the basis how they perform heat and/or mass transfer analyses. Finally, this chapter defines the most important parameters used by previous models, which were implemented into our modeling efforts.

The thermal performance of green roofs has been investigated worldwide using three different approaches: (1) field or laboratory experimentation, (2) theoretical/numerical studies, and (3) a combination of laboratory or field experiments with numerical models. Field experimental studies have focused on measuring heat flux reduction, green roof R-value, and/or evapotranspiration under unsteady weather conditions and using field instrumentation. In contrast, there are only few laboratory studies focused on quantifying the same physical processes. These laboratory studies tried to minimize transient phenomena with better controls of the environment and to improve the accuracy of data sets with better laboratory-rated instrumentation. However, field or laboratory experimentation has the limitation of representing only a few different climates or building designs. This limitation can be complemented by adding modeling capabilities into a research project.

Modeling the thermal performance of green roof is challenging due to the complex heat and mass transfer through the roof resulting from the shading, insulation, evapotranspiration, and
thermal mass (Liu, 2004). As a result, the modeling of green roofs is not an easy task because the thermal properties of a green roof depend on variable factors such as the plant growth, substrate, and water content in the substrate. To the best of our knowledge, the first modern theoretical green roof model was developed in India (Nayak et al. 1982). Since then, researchers have modeled green roofs by using steady-state R-values and/or by adjusting the radiative/spectral properties of the roof to account for plant materials. More robust models have implemented energy and mass balance across the roof and calculated evapotranspiration. Some of these models were validated with field data. At first, most of the studies used simple approaches to model green roofs. As published research findings gradually increased the understanding of transport processes for green roofs, more complicated models were created.

3.1 Steady State R-Value

This particular approach to model green roofs typically uses a constant R-value to represent the influence of green roof on the overall heat transfer. This green roof R-value is added to the total R-value of the other roof assembly materials. An early approach calculated the increase in the R-value and reduction of thermal losses due to temperature differences across the building envelope using design temperatures (Eumorfopoulou et al. 1998). Another study performed transient simulations of several insulated and/or non-insulated roofs with and without green roofs adding an additional R-value for the roof (Nichau et al. 2001). In principle, buildings with green roofs had higher thermal benefits when the rest of the roof assembly had low insulation values. Finally, another study conducted transient annual simulations for different roof configurations (Wong et al. 2003). In this study, a green roof with a higher LAI (Leaf Area Index) results in higher energy savings. In contrast, the computations with different soil depths/water content showed that a green roof with dry soil had lower energy savings (Wong et al. 2003).
reason for that is probably because the model did not include evapotranspiration transport phenomenon when the soil is wet. Therefore, this model underestimates the performance when the roof was wet. All of these models represent early approaches to modeling of green roof because they simplified the heat and mass transfer processes in a green roof to a point where the studies neglected important physical phenomena.

3.2 Modified Radiative Properties

Others models have included plant shading factors based on observation of the importance that shading has on the green roof thermal performance (Bass et al. 2003, Liu et al. 2004). However, these models did not include evapotranspiration and a variable thermal conductivity for the substrate, which can account for substantial heat flux changes in certain climates (Nayak et al. 1982, Kumar and Kaushik 2005, Tabares-Velasco et al. 2009a). Slightly more detailed models consist of constant latent heat flux and/or photosynthesis rate in an equivalent albedo combined with measured thermal conductivities (Hilten 2005, Saiz Alcazar 2005, Saiz Alcazar and Bass 2005). However, these models are still not implementing an energy balance across the green roofs to fully quantify all the important heat and mass processes. Thus, these models still lack some of the fundamental transport phenomena to properly model the performance of green roofs. To overcome these deficits of the previous models, researchers have also created more complex models to analyze the thermal performance of green roofs. These models are typically based on time-dependant solutions of the unsteady heat conduction equation and, can be classified depending on whether they implement only an energy balance or a full energy and mass balance across the green roof.
3.3 Models Implement Heat and/or Mass Balance

Research studies have created more robust models to analyze the thermal performance of green roofs performing heat and/or mass transfer analyses. These models typically include solutions of the unsteady heat conduction equation, although some use quasi-steady state conditions. The common assumptions made by these theoretical thermal models are:

1. Plants and green roof substrate are horizontally homogeneous
2. Heat and mass transfer are vertical, while horizontal fluxes are negligible
3. Air beneath stomata is saturated
4. Biochemical reactions of plants (photosynthesis) result in negligible heat fluxes
5. Conduction heat transfer in plants is negligible
6. Plants are well irrigated, healthy, and in the fully grown stage
7. Water distribution within the canopy is homogeneous
8. Plant-soil layer is free from mulch, and
9. Green roof substrate is completely covered by plants.

The most common assumptions are horizontally homogeneous roof materials and vertical heat and mass fluxes. These two assumptions significantly simplify models by limiting the problem to one dimension. The next three assumptions, numbered as 3, 4, and 5, simplify heat transfer processes related to plant biology because plants are very complex systems and their role in the overall energy balance are minimal. Assumptions number 6 and 7 are also commonly used and presume that the volumetric water content (VWC) in the substrate does not change with time, as the green roof is irrigated. As a result, there are no changes in the thermal properties of the substrate, or in the canopy resistance due to water stress. These assumptions make the modeling of green roofs simpler because the mass balance is easier to implement by eliminating the need to calculate the water losses due to drainage and evaporation, as well as the water gains due to the
precipitation. In reality, plants are watered during the establishment period, typically during the first year of planting. Beyond this initial growth phase, irrigation depends on the local rainfall and weather, and in some cases plants may not need supplemental irrigation at all (Snodgrass and Snodgrass 2006). Thus, variation in the water content in the substrate and plant coverage is expected for typical extensive green roofs and will be implemented in modeling efforts in the present study. Assumption 8 implies that green roof substrate is primarily responsible for substrate evaporation, and no munch is attenuating the vapor transfer to the environment. Finally, assumption 9 is very common because in many practical applications LAI or plant coverage is not known. Table 3-1 summarizes the review of the green roof models that implement heat and/or mass balance.

As shown in Table 3-1, couple of models discretized the green roof in three or more nodes within roof layers to apply an energy balance in each node. Furthermore, some of the models include water transport in the soil, and only one of the models accounts for changes in the water content of the growing media due to evapotranspiration and rain. Evapotranspiration is mainly calculated by the Vapor Pressure Deficit (VPD) method (Nayak et al. 1982, Palomo del Barrio 1998, Lazzarin et al. 2005, Alexandri and Jones 2007, Sailor 2008). Nevertheless, each study uses different resistance functions to calculate evapotranspiration. Finally, all of these models execute an overall energy balance, others perform heat and mass balance on individual roof layers. These differences will be address more extensively in the two upcoming sections.
Table 3-1: Overview of the existing theoretical green roof models.

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<tbody>
<tr>
<td>ET</td>
<td>VPD &amp; vapor resistance</td>
<td>VPD &amp; vapor resistance</td>
<td>Evaporative Efficiency &amp; Humidity difference</td>
<td>Bowen ratio</td>
<td>VPD &amp; wind correlation</td>
<td>VPD &amp; vapor resistance</td>
<td>VPD &amp; wind correlation</td>
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<td>Assumptions</td>
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<td>Evaporative Efficiency</td>
<td>9</td>
<td>1,2</td>
<td>1,2,6,7</td>
<td>1,4</td>
</tr>
<tr>
<td>Roof Discretization</td>
<td>Two soil layers, Plants</td>
<td>Multiple nodes</td>
<td>No</td>
<td>No</td>
<td>Multiple modes</td>
<td>Plants, soil, roof</td>
<td>Soil, Plants</td>
</tr>
</tbody>
</table>

* Detailed descriptions of the eleven most common model assumptions are available on pages 10
3.3.1 Green Roof Models Implement Heat Balance


Evapotranspiration is calculated by using a convective mass transfer coefficient with no stomatal or substrate resistance (Nayak et al. 1982, Howe 2008) or by the Bowen ratio with values obtained from field measurements (Gaffin et al. 2006). Only one of these models performed a surface temperature validation (Gaffin et al. 2005, Gaffin et al. 2006), while another study mentioned verification process by matching surface temperature trends with previous field studies, but did not specify the results or procedure (Howe 2008). Based on many of these studies, comparison was made among different roofing technologies. Green roofs perform among the best roofing technologies for heat flux reduction across the roof compared to other technologies (Nayak et al. 1982, Gaffin et al. 2005, Howe 2008). However, these models are based on the assumption that evapotranspiration is not directly related to water content. This statement while convenient for simulation purposes, it is not accurate for green roofs that are not irrigated.

Another green roof model could potentially overcome this issue (Palomo del Barrio 1998). This model set the heat and mass balance equations for the substrate model. However, the
report only analyzed the case with constant substrate water content. Thus, neglecting the role substrate water content has on stomatal and substrate resistance. The model is one of the most referenced models, and it has been validated with surface temperature values by two other studies (Theodosiou 2003, Kumar and Kaushik 2005). All three models agreed that LAI plays one of the most important roles in reducing heat flux through the roof as LAI is included in convective heat transfer, shading and evapotranspiration. This statement agrees with another model (Takahura et al. 2000). However, there are disagreements regarding the role of substrate thickness. In one study, substrate thickness has a major role (Palomo del Barrio 1998), while in another study this role is not significant (Theodosiou 2003). From the three studies (Palomo del Barrio 1998, Theodosiou 2003, Kumar and Kaushik 2005) only the original source (Palomo del Barrio 1998) analyzed the performance of a green roof under two different substrate water contents. This study found lower heat fluxes through the roof when the green roof was wet compared to a dry green roof. The lower heat flux in a wet green roof was mainly attributed to an overall decrease in thermal diffusivity, with evapotranspiration having a secondary role (Palomo del Barrio 1998).

In general, these models represent the physical phenomena better than the previous simpler models. However, green roofs are a technology where heat and mass transfer processes are taking place simultaneously; therefore, these models still lack the water-energy interrelation and the role of plants and substrate to hold and evaporate water. However, these studies have shown that LAI plays an important role, although the role of the soil depth and volumetric water content is not entirely clear.
3.3.2 Mass and Energy Balance

A couple of models have simulated green roofs by coupling heat and mass transfer processes. One model took into account water movement in the substrate, but it required knowledge of water content changes, and it did not consider precipitation (Takebayashi and Moriyama 2007). Overall, the study concluded that green roof reduced the sensible heat flux contributing to urban heat island effect by diverting the heat into evapotranspiration, in contrast with a high reflective roof that increase the albedo of the surface (Takebayashi and Moriyama 2007). Looking also into the urban heat island effect, another study concluded that adding mass transfer into the analysis improved convergence with data of surrounding air (Alexandri and Jones 2007). In addition, this study found that stomatal resistance is an important factor in the heat and mass transfer processes. As a result, both heat and mass transfer processes need to be addressed simultaneously. However, the model did not consider rainfall or irrigation. Another model has considered precipitation in their analysis. This model grouped convective and radiative heat transfer into an adduction coefficient and calculated evapotranspiration using the Penman equation, a previous model before Penman-Monteith equation that does not contain stomatal resistance. Thus, the model obtained relative success when the roof was wet but not in dry conditions because the Penman equation does not contain stomatal resistance (Lazzarin et al. 2005).

A recent green roof model (Sailor 2008) presented an adaptation of soil-vegetation-atmosphere transfer (SVAT) schemes used in mesoscale meteorological analysis or general circulation models (Pielke 2002). Their parametric study showed soil thickness and LAI can have energy savings in winter and summer, but negative impacts in winter due to evapotranspiration.
However, high LAI values in winter are uncommon, as many plants will go dormant, thus losing their leaves, thus decreasing their LAI.

Overall previous green roof models have conducted heat and/or mass balance across green roofs to quantify the physical phenomena. There are some similarities and differences among the models. To completely analyze and learn from these previous studies, it is important to compare how each of the most representative models model heat and mass transfer phenomena.

3.4 Comparison of Heat and Mass Transfer Processes

Table 3-1 and Section 3.3 describe the previous green roof models and some of their main conclusions and assumptions used. However, to properly develop a new green roof model, it is also important to fully understand how the most representative green roof models quantify each of the heat and mass transfer phenomena. Consequently Table 3 compares green roof models that represent approaches targeting evaluation of all important heat and mass transfer processes. Most important distinguishing characteristics of different models include:

- the substrate evaporation resistance
- the plant transpiration resistance
- substrate thermal conductivity, and
- the convective resistance to mass and heat transfer.
**Table 3-2**: Comparison of heat and mass transfer functions used in green roof models.

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<tr>
<td>Short-wave Radiation</td>
<td>Beer’s Law</td>
<td>Beer’s Law</td>
<td>Beer’s Law</td>
<td>Beer’s Law</td>
</tr>
<tr>
<td>Long-wave Radiation</td>
<td>Plant – Sky</td>
<td>Plant - Sky</td>
<td>Adduction coefficient</td>
<td>Plant - Sky</td>
</tr>
<tr>
<td></td>
<td>Substrate - Sky</td>
<td>Substrate - Sky</td>
<td></td>
<td>Substrate - Sky</td>
</tr>
<tr>
<td></td>
<td>Substrate - Plants (infinite plates)</td>
<td>Substrate - Plants (plants surrounding substrate)</td>
<td></td>
<td>Substrate - Plants (plants surrounding substrate)</td>
</tr>
<tr>
<td>Convection</td>
<td>1.1 factor + Logarithmic profile + instability factors + LAI</td>
<td>Logarithmic profile</td>
<td>Adduction coefficient</td>
<td>2 Factor + Empirical equation for aerodynamic resistance based on plant characteristics + LAI</td>
</tr>
<tr>
<td>Evapotranspiration</td>
<td>VPD for plants and soil covered/uncovered</td>
<td>VPD for plants and soil covered</td>
<td>Penman Equation</td>
<td>VPD for plants and soil covered</td>
</tr>
<tr>
<td>Stomatal Resistance</td>
<td>$r_s = r_s(VWC, \text{Sun})$ (multiplicative)</td>
<td>$r_s = r_s(VWC, \text{Sun})$ (additive)</td>
<td>Empirical wind equation</td>
<td>$r_s = r_s(\text{Sun, Temp, VPD, CO}_2)$ (multiplicative)</td>
</tr>
<tr>
<td>Substrate Resistance</td>
<td>Alpha method (see 2.3.2)</td>
<td>$r_{soil} = r_{soil}(VWC,VWC_{sat})$</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Substrate Thermal Conductivity</td>
<td>N/A</td>
<td>Exponential function depending on VWC</td>
<td>N/A</td>
<td>Power + exponential function depending on density and VWC</td>
</tr>
</tbody>
</table>
3.5 Conclusions

Previous green roof models were reviewed and compared depending on their characteristic and their results. While models agree that LAI plays an important role at reducing heat flux through the roof, there is disagreement about the role of substrate depth. Overall, most complete green roof models tend to model the behavior of plant stomata to control water and the resistance of substrate/soil to lost water. Radiative heat exchanges between the three surfaces (sky, plants, and substrate) are also included. A complete green roof model should cover all of the relevant heat and mass transfer phenomena as well as their interactions. The main differences between models are: (1) factors affecting stomatal resistance, (2) convective heat transfer coefficient, (3) convective heat transfer multiplicative factor, and (4) substrate thermal conductivity. In order to face these differences, it is necessary to experimentally quantify heat and mass transfer processed so that modeling and laboratory work can address the remaining unanswered questions.
Chapter 4

Existing Experiments

The main reason for using an experimental approach in studying green roofs is its reliability and simplicity as long as an experimental setup is available. Previous field studies have followed different approaches based on field experimental studies that measured: (1) heat flux reduction through the roof, (2) green roof R-value, and (3) evapotranspiration under unsteady weather conditions. Additionally, there have also been few laboratory studies focused on quantifying the same physical processes. Chapter 4 will describe the most relevant experimental studies and assess if there is enough experimental data to properly develop and validate a green roof model.

4.1 Heat Flux

To the best of our knowledge, the first thermal measurements for green roofs were collected in Germany during the 1970’s. However, these data sets included only sparse temperature recordings on a green roof and a bitumen roof (Hoeschele and Schmidth 1977). The first field studies focused on energy savings due to green roofs were mainly performed for intensive green roofs (Minke et al. 1982, Liesecke et al. 1989, Christian et al. 1996).

More recent field experimentation studies of extensive green roofs in North American have compared the thermal performance of green roofs with reference roofs for different period lengths: from a couple of weeks during summer season to one to two years. Average heat flux reduction through the studied green roofs varied from 18% to 75%. Different results could be

Interestingly, a field study found a significant reduction of heat flux from a green roof compared to a bare soil roof (Wong et al. 2003). The study concluded that the difference was due to the shading of plants because the heat flux at night was mainly the same for both roofs. Another study came to similar conclusions by analyzing an irrigated bare soil roof, and then by adding a shading device over the roof (Pearlmutter and Rosenfeld 2008). Our present laboratory study finds that it is not just the shading, but also the evapotranspiration that improves the thermal performance of the green roof by the presence of plants. This finding was possible because we conducted tightly controlled laboratory experiments with laboratory graded instrumentation (Tabares-Velasco and Srebric 2009b).

It is important to mention that there has been a substantial research focus on the ability of green roofs to decrease roof surface temperatures when compared to traditional bituminous roofs. Measurements of roof surface and environmental air temperatures are important because they may help evaluate how green roofs decrease the heat flux, and the urban heat island effect. These temperatures are also useful as data for model validation. Nevertheless, from a building energy performance perspective, the main goal is to analyze heat transfer through a green roof and building envelope. Finally, other studies have focused their effort in calculating an R-value for green roof systems.
4.2 R-value

Green roofs can reduce the heat flux through a roof by increasing the insulation value or thermal resistance (R-value) of the roof. However, because of different layers, as well as heat and mass transfer processes in green roofs, the thermal resistance cannot be modeled with a simple R-value used for conventional insulation materials. Previous studies have measured the R-value of green roofs that fluctuates depending on the amount of moisture, the type of substrate, and the weather conditions (Liesecke et al. 1989). Calculated R-values for extensive green roofs measured in field and laboratories experiments varied from 1.8 to 4.8 ft² h °F/Btu (Wong et al. 2003, Bell and Spolek 2009, Tabares-Velasco and Srebric 2009a), while published R-values for intensive green roof varied between 5 and 20 ft² h °F/Btu (Minke et al. 1982, Wong et al. 2003). The difficulty in measuring and then calculating the R-value was due to the non-steady state conditions during the test period (Perino et al. 2003, Perino et al. 2003b).

4.3 Evapotranspiration

Previous research has shown that moisture content in the substrate plays an important role in decreasing the surface green roof temperature and heat flux through the roof by means of evapotranspiration (Liesecke et al. 1989, Liu and Baskaran 2004, Lazzarin et al. 2005, Nyuk Hien et al. 2007). Evapotranspiration is the combined process of water loss from the soil (evaporation) and plants (transpiration). As reviewed in the literature (Rana and Katerji 2000), there are three general methodologies to measure evapotranspiration. Each methodology has different techniques to measure evapotranspiration:

1. Hydrological
   a. Lysimeter
   b. Soil water balance
2. Micrometeorological
There are two hydrological approaches: soil water balance and lysimeters. As the name suggests, the first method measures evapotranspiration indirectly by making a soil water balance. The soil water balance is performed by tracking changes in the soil water content that can be measured with probes using different methods such as the time domain reflectometry (TDR). Employing TDR method can be used for hourly evapotranspiration measurements. Alternatively, weighing lysimeters directly measure evapotranspiration by using a load sensor or scale. The load sensor measures weight changes due to evapotranspiration, with an accuracy of 10-20% for the hourly time scale (Rana and Katerji 2000).

The second methodology, micrometeorological measurement, is based on the energy balance, thus, it measures latent heat fluxes. The techniques are: energy balance/Bowen ratio, aerodynamic method, and eddy covariance. However, due to theoretical assumptions embedded in the required instrumentation, they can only be used in large flat areas with uniformly distributed vegetation (Rana and Katerji 2000).

The third group, plant physiology method, includes the sap flow method and the chamber system method. The first technique determines transpiration by measuring sap flow, while neglecting soil evaporation. The chamber system method consists of an enclosed chamber made of glass or plastic films. Evapotranspiration is calculated based on the difference in the humidity content of the air entering and leaving the chamber. Uncertainties around 10% are cited; however,
due to intrinsic problems, such as decreased solar radiation, air speed and temperature inside of a chamber, the evapotranspiration measurement accuracy can be further reduced (Rana et al. 2000).

In previous green roof studies, most researchers have measured evapotranspiration rates using hydrological methods (VanWoert et al. 2005, Rezaei 2005, Berghage et al. 2007). A lysimeter has been the most common measurement approach (Schmidt 2003, Koehler 2004, Rezaei 2005, Berghage et al. 2007). A few studies have used TDR or humidity sensors in the substrate (VanWoert et al. 2005, Takebayashi and Moriyama 2007). Some have emphasized calculations of energy savings due to evapotranspiration (Schmidt 2003, Koehler 2004, Takebayashi and Moriyama 2007). In summer conditions, a study calculated that evapotranspiration from the green roofs absorbed 12% to 25% of the incoming heat flux, for a dry and wet green roof, respectively (Lazzarin et al. 2005). These results show the importance of evapotranspiration in the reduction of thermal loads on the roof. Figure 4-1 shows evapotranspiration rates for early summer conditions in a greenhouse in Pennsylvania (Rezaei 2005). The evapotranspiration rates and corresponding heat fluxes are measured based on the lysimeter method. The highest evapotranspiration heat flux was around 350W/m² of roof surface area during the peak solar radiation on the first day of measurements, when the substrate was the wettest in this experiment. The study showed that not only does evapotranspiration reduce the thermal loads, but also that the heat fluxes reduction is the highest during the peak loads.
This study showed the advantages of testing a green roof inside a greenhouse. This greenhouse study represents a scenario between laboratory and field studies, because the researchers were able to control some environmental parameters, such as air temperature, while the other parameters were uncontrolled, such as incoming solar radiation (Rezaei 2005, Berghage et al. 2007). Previous studies have used similar approaches by installing open or closed chambers in outdoor conditions to calculate soil evaporation (van de Griend and Owe 1994, Aluwihare and Watanabe 2003). The reason for these efforts is due to the fact that field experiments have the advantage of measuring different heat fluxes under realistic environmental conditions. However, outdoor instrumentation tends to be less accurate when compared to laboratory rate instrumentation. Moreover, the task of controlling an outdoor environment during field experimentation becomes a tremendous challenge. Therefore, different research groups have proposed the use of laboratory experiments for green roofs or soil evaporation studies.

Figure 4-1: Evapotranspiration rates for early summer conditions in Pennsylvania (Rezaei, 2005).
4.4 Existing Laboratory Experiments

Laboratory green roof experiments have previously been performed in wind tunnels or environmental chambers. They all differ from field experiments because artificial lighting is provided and environmental parameters, such as air temperature, humidity and solar radiation, are controlled. This approach has been used successfully to combine a wind tunnel experimental approach with lysimeter measurements for soil evaporation studies (Yamanaka et al. 1997).

Two laboratory experiments have evaluated green roof thermal performance in a wind tunnel (Onmura et al. 2001, Bell and Spolek 2009). A wind tunnel study in Japan investigated the evaporative cooling effect of the green roof (Onmura et al. 2001), while the other wind tunnel study calculated R-values for green roof samples in the United States (Bell and Spolek 2009). Both studies reported challenges in simulating outdoor environmental conditions. For example, in the first study, solar radiation was simulated with infrared lamps; thus, the spectral power distribution of the lamps was low in the visible and PAR (Photosynthetically Active Region) region and high in the infrared spectrum. In the second study, high intensity discharge lamps were used with irradiance at the green roof samples around 100 W/m². None of these studies were able to measure evapotranspiration rate continuously. Nevertheless, the first study measured the total amount of evaporated water over the 67 hour period of time. This shows that evapotranspiration was one of the most influential mechanisms in the overall heat transfer, even though the heat flux reduction due to evapotranspiration was not quantified (Onmura et al. 2001).

Another study had followed a different approach using a small chamber to evaluate the thermal reduction effect of plants on rooftops (Fang 2008). The experiment used a small chamber
with 500W lamps to test different plants. However, the study only measured thermal reduction rate in terms of decrease of surface temperature and surrounding air when plants were present.

In summary, the previous green roof studies represent a step towards more controlled experimentation. However, none of these studies measured continuously evapotranspiration, an important variable in the heat and mass transfer process on a green roof. To properly quantify and evaluate the important heat and mass transfer phenomena in a green roof, it is vital to measure all of them in a controlled environment.

4.5 Conclusions

Previous field and laboratory studies have proved that green roofs can significantly decrease the heat flux through the roof. Some of these studies have concentrated their efforts on measuring: (1) evapotranspiration, (2) heat flux through the roof or (3) calculating the R-value. Evapotranspiration is found to play a major role in controlling heat gains through the roof. However, to the best of our knowledge, there is no single study that has measured all of the important heat and mass transfer processes simultaneously. This represents a challenging task that is required in order to completely develop and validate a green roof heat transfer model. A new experimental apparatus should be able to measure radiation, convection, evapotranspiration and conduction heat fluxes simultaneously.
Chapter 5

New Experimental Setup: “Cold Plate” Apparatus

Based on the literature review findings presented in Chapter 4, a new experimental apparatus was needed to address shortcomings in the existing data sets on energy balance for green roofs. A new apparatus, named “Cold Plate,” was designed to include laboratory-rated instrumentation and allow simultaneous measurements of all important heat and mass transfer processes on a green roof. Thus, Chapter 5 describes the characteristics of the new “Cold Plate” apparatus designed and built as part of this research project. The “Cold Plate” apparatus is located inside a full-scale environmental chamber. This new apparatus enabled experiments isolated from stochastic outdoor conditions. The controlled environmental conditions included airflow rate, temperature, and humidity, which represent quasi steady-state air parameters in outdoor environment.

5.1 “Cold Plate” Apparatus Description

The design and construction of experimental apparatus for testing green roof thermal properties was a challenging process that included several versions of the apparatus. The first version of the apparatus used standard output fluorescent lamps and did not include a scale or water content sensors (Tabares-Velasco et al. 2007). The final version of the apparatus requires the use of controlled environmental conditions provided by the environmental chamber. The design of the new apparatus was inspired by ASTM standards C177 and C1363, which respectively govern “hot plate” and “hot box” tests for material thermal properties (ASTM C
The final version of the apparatus was named “Cold Plate,” which uses the chamber to control environmental parameters, and a bank of lamps to serve as a radiative heat source. Consequently, the environmental chamber eliminates most of the non-steady state problems encountered in the field experimentation, and allows use of laboratory-rated acquisition equipment. A schematic representation and a photo of the “Cold Plate” apparatus inside the environmental chamber are shown in Figure 5-1 and Figure 5-2, respectively.

Figure 5-1. Schematic representation of “Cold Plate” apparatus inside the environmental chamber.
As shown in Figure 5-1 and Figure 5-2, solar radiation is simulated with a bank of very high output (VHO) fluorescent lamps. The box, supporting the green roof sample, is well insulated on the sides ($R \approx 60 \text{ ft}^2 \text{ h} \, ^\circ\text{F}/\text{Btu}$) to maintain a one-dimensional heat flux. Below the green roof sample, the cold plate is maintained at constant and quasi-uniform temperature with a hydronic system supplying cold water at a constant flow rate and temperature. Underneath the box, a platform is continuously measuring the weight of the green roof sample. Finally, the remaining environmental properties, such as air temperature, airflow velocity, and relative humidity, are set using the HVAC control system in the environmental chamber. However, to achieve higher air velocities, a set of fans were added to the chamber for the tests that required higher air velocities for assessment of convective heat and mass transfer.
The “Cold Plate” apparatus is instrumented with different data acquisition sensors. Figure 5-3 and Figure 5-4 show locations of several data acquisition sensors installed in green roof samples. The measured parameters of interest are:

1. **Evapotranspiration rate** – Measured by two different approaches: (1) changes in weight of the green roof sample due to water losses using a platform, and (2) changes in volumetric water content in the substrate due to water losses. A third approach to measure evapotranspiration was tested in a previous version of the “Cold Plate.” This previous version used a modification of the chamber method explained in Chapter 4 by measuring the supply and exhaust air humidity. However, this approach did not work due to the chamber size and air humidifier controls.

2. **Incident incoming short-wave radiation** – Measured by a secondary class (best accuracy possible, ISO 9060 classification) pyranometer with spectral range of 310-2800 nm.

3. **Incident incoming long-wave radiation** – Measured by a laboratory-rated pyrgeometer with spectral range of 4500-42000 nm. The long wave measurements are confirmed by simplifying the complex radiative heat exchanges between multiple surfaces in the chamber. The proposed simplified model is based on a radiative heat analyses among three surfaces: (1) lamps, (2) plants and (3) chamber walls surrounding green roof sample.

4. **Outgoing long-wave radiation** – Calculated by measuring the average surface temperature of the plants and substrate and using a proper emissive of 0.97 for plants (Monteith and Unsworth 2008) and 0.95 for substrate (Pielke 2002).

5. **Heat flux through the green roofs** – Measured by heat flux meters and by making an energy balance around the “Cold Plate.” The energy balance method consists of measuring the incoming and outgoing “Cold Plate” water temperature and flow rate of the hydronic system.

6. **Convective heat transfer** – Calculated by subtracting all heat flows in energy balance Equation (1).

7. **Substrate top and bottom layer temperature** – Measured by a set of 5 thermistors located under a thin layer of substrate to measure the top substrate temperature. Another 5 thermistors were located at the bottom of the substrate layer in contact with the filter cloth membrane.
8. Plant temperature – Measured by 5 thermistors attached to leaves. An infrared camera was used during the last day of experiments to confirm the surface temperature values.

9. Substrate volumetric water content – Measured by water content reflectometers located inside the green roof substrate to measure the volumetric water content in the green roof substrate.

10. Air velocities – Measured by hot-sphere anemometers at different position and heights. The same sensors also measured air temperature at the “Cold Plate.”

11. Room air relative humidity and temperature – Measured by humidity and temperature sensors located in the return ductwork.

12. Spectral reflectivity of the green roof sample – Measured with a spectroradiometer. For the case of substrate, a variable albedo for the specific wavelength of the lamps was obtained from the literature for different soils and plants (Escadafal 1990, La et al. 2008, Gates 1980).

13. Leaf Area Index (LAI) – Measured manually by leaf counting in several grid points (Figure 5-4) for sample with Delosperma nubigenum. LAI for sample with Sedum spurium was obtained using: (1) FAO equation depending on plant height and (2) correlation between normalized difference vegetation index (NDVI) and LAI for several ecosystems such as tundra and desert. NDVI is a ratio of spectral surface reflectance for red and near-infrared radiation, which gives an estimate of vegetation cover or LAI (Jones 1992).

Figure 5-3. Outline of data sensor locations for tested green roof samples.
From the previous list of 13 variables measured, evapotranspiration and conductive heat flux are measured by two independent approaches to add redundancy and check for the accuracy of both measurement methods. This focus is due to the fact that evapotranspiration has a major role in the heat and mass transfer phenomena in green roofs. Overall, the “Cold Plate” apparatus represents a new kind of apparatus that measures all of the important heat fluxes observed in the quasi-steady state heat and mass transfer analyses. Section 5.2 will describe the tested samples as well as the procedure followed to ensure quasi-steady state conditions.

5.2 Green Roof Samples

Green roof samples were initially grown in a greenhouse at the Pennsylvania State University and later moved into the environmental chamber, as shown in Figure 5-5. Green roof planter boxes have outer dimensions of 1.30 m by 1.1 m. Substrate depth was around 0.09 m. The
planter boxes were built to meet ASTM standards C117 and C1363 that require large surface areas compared to sample thickness to produce a one-dimensional heat flux (ASTM C 1363-97, ASTM C 177-97). In addition, only the center part of the green roof sample was used for thermal measurements. The outer part was used as a buffer zone where 1-dimensional flux cannot be safely assumed.

![Green roof planter boxes](image)

Figure 5-5. Green roof planter boxes inside a greenhouse at the Department of Horticulture, The Pennsylvania State University.

The substrate used in the green roof planter boxes consisted mainly of expanded clay. Substrate porosity was estimated to be around 55% and field capacity around 34% (Denardo 2003). Density of substrate was calculated to be 640 kg/m$^3$, similar to other reported green roof substrate densities (Denardo 2003, Rezaei 2005, Sailor et al. 2008). Plants selected for this experimentation were *Delosperma nubigenum* and *Sedum spurium*. These drought tolerant species were selected as they are typical plants used on extensive green roofs. These two species are hardy, succulent plants and have the ability to survive in drought conditions by limiting their water loss due to transpiration (Snodgrass and Snodgrass 2006). Figure 5-6 shows planter boxes inside the environmental chamber.
5.3 Environmental Conditions and Experimental Procedure

One of the objectives of this research is to assess the role of plants in the reduction of heat flux through a green roof. Thus, three different green roof samples were tested: (1) green roof sample without plants, (2) green roof sample with *Sedum spurium*, and (3) green roof sample with *Delosperma*. The sample without plants was tested to compare heat fluxes between the samples without plants and the samples with plants. This comparison is used to address whether plants need to be included in a green roof model. The samples with plants were tested under different environmental conditions to observe their heat and mass transfer performance. Two different types of lamps were used: (1) 165W UVA tanning lamps and (2) 160W VHO Daylight Fluorescent lamps. The UVA lamps provide a higher irradiance. However, the amount of UVA radiation was significantly more than what is naturally available outdoor. Thus, plants started to wilt after a single 3-day test. Therefore, the remaining experiments with plants used Daylight Fluorescent. These types of lamps have an almost constant wavelength output in the visible range compared to the Cool White or Warm White that have a higher output in the yellow-orange-red range.
part of the spectrum (Ryer 1997). Table 5-1 and Table 5-2 show design of environmental conditions for scheduled experiments with and without plants. For each experiment, one of the following environmental variables was changed at a time: (1) relative humidity, (2) solar radiation, (3) air temperature, (4) air speed, and (5) plant type. This was done to quantify differences due to the green roof thermal performance.

**Table 5-1**: Summary of environmental conditions for green roof experiments with plants

<table>
<thead>
<tr>
<th>Test</th>
<th>Room Temperature (°C)</th>
<th>Relative Humidity (%)</th>
<th>Solar Irradiance (W/m²)</th>
<th>Air Speed (m/s)</th>
<th>Plant Type</th>
<th>Light Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Baseline</td>
<td>28.0</td>
<td>30</td>
<td>100</td>
<td>0.10</td>
<td>Delosperma</td>
<td>Fluorescent</td>
</tr>
<tr>
<td>2. Humidity</td>
<td>28.0</td>
<td>50</td>
<td>100</td>
<td>0.10</td>
<td>Delosperma</td>
<td>Fluorescent</td>
</tr>
<tr>
<td>3. Solar</td>
<td>28.0</td>
<td>30</td>
<td>70</td>
<td>0.10</td>
<td>Delosperma</td>
<td>Fluorescent</td>
</tr>
<tr>
<td>4. Speed</td>
<td>28.0</td>
<td>30</td>
<td>100</td>
<td>1.00</td>
<td>Delosperma</td>
<td>Fluorescent</td>
</tr>
<tr>
<td>5. Temperature</td>
<td><strong>26.0</strong></td>
<td>30</td>
<td>100</td>
<td>0.10</td>
<td>Delosperma</td>
<td>Fluorescent</td>
</tr>
<tr>
<td>6. Temperature</td>
<td><strong>24.0</strong></td>
<td>50</td>
<td>100</td>
<td>1.00</td>
<td>Delosperma</td>
<td>Fluorescent</td>
</tr>
<tr>
<td>7. Baseline</td>
<td>28.0</td>
<td>30</td>
<td>100</td>
<td>0.10</td>
<td>Delosperma</td>
<td>Fluorescent</td>
</tr>
<tr>
<td>8. UVA</td>
<td>28.0</td>
<td>30</td>
<td>160</td>
<td>0.10</td>
<td>Sedum</td>
<td>UVA</td>
</tr>
<tr>
<td>9. Low LAI</td>
<td>28.0</td>
<td>30</td>
<td>100</td>
<td>0.10</td>
<td>Sedum</td>
<td>Fluorescent</td>
</tr>
</tbody>
</table>

**Table 5-2**: Summary of environmental conditions for green roof experiments without plants

<table>
<thead>
<tr>
<th>Test</th>
<th>Room Temperature (°C)</th>
<th>Relative Humidity (%)</th>
<th>Solar Irradiance (W/m²)</th>
<th>Air Speed (m/s)</th>
<th>Plant Type</th>
<th>Light Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>UVA</td>
<td>28.0</td>
<td>30</td>
<td>160</td>
<td>0.10</td>
<td>No Plants</td>
<td>UVA</td>
</tr>
<tr>
<td>Fluorescent</td>
<td>28.0</td>
<td>30</td>
<td>100</td>
<td>0.10</td>
<td>No Plants</td>
<td>Fluorescent</td>
</tr>
</tbody>
</table>

Table 5-1 shows a Baseline case scenario, which represents the benchmark case. The Baseline experiment was replicated twice for controlling purposes. The Baseline scenario targeted dry bulb temperature and relative humidity equal to 28°C and 30%. This condition is similar to the Annual Cooling Design conditions for San Francisco, California (ASHRAE 2005).
Samples were watered until saturation 48 and 24 hours before starting the experiments. Once experiments started, the environmental chamber was closed to minimize any interactions with the surrounding environment. Lamps were programmed to turn on/off at the same time each day. All tests had 14 hours of artificial lighting and 10 hours of darkness, except from the UVA experiments, during which there was an equal time of artificial lighting and darkness. These “day/night” cycles created cooler temperatures during the dark periods to simulate outdoor conditions as shown in Figure 5-7. Data from the last three hours of “daylight” were used to calculate steady-state values for all of the heat transfer processes. Quasi steady state conditions were obtained at the end of the daylight period for most measure variables.

![Chamber Return Air Temperature](image)

Figure 5-7. Return air temperature in the environmental chamber during baseline experiment.

As shown in Figure 5-7, the temperature inside the chamber remains almost constant at 28°C during “daylight” hours. The constant surrounding temperatures along with steady short-wave radiation from the lamps provided the adequate conditions to obtain quasi steady state heat and mass transfer processes. Interestingly, evapotranspiration fluxes achieved steady state
conditions a few hours after the lights were on, once the environmental parameters stabilized. Other variables such as heat flux through the green roof and substrate temperature achieved steady state conditions near the end of the daylight period. Thus, the time constant for the green roof samples was also calculated based on the amount of time for heat fluxes through the green roof sample to achieve steady-state conditions. The time constant ($\tau$) is a measure of how a system responds to environmental changes. In this thesis the time constant was defined as: (1) time required for the initial heat flux to increase 2/3 of the difference between the heat flux at the beginning of the day and the quasi-steady state value and (2) as defined in the literature,

$$\tau = \rho \cdot Volume \cdot C_p / h \cdot Area$$

(Incropera and. Dewitt 2002). The calculated time constant using definition (1) varied from 3.9 hours to 6 hours having an average of 4.9 hours. The calculated time constant using definition (2) was about 4.3 hours. However, the time constant could be as low as 1-2 hours at actual roof conditions when the wind speed and convective heat transfer coefficient are higher.

5.4 Conclusions

The “Cold Plate” apparatus represents a new kind of apparatus that measures all of the important heat fluxes observed in the quasi-steady state heat and mass transfer analyses for a green roof. Experiments were conducted in a full-scale environmental chamber that simulated outdoor conditions. Up to date, there is no other experimental apparatus that simultaneously measures the same physical phenomena. Data obtained from these experiments are analyzed in Chapter 6 and used in Chapter 8 to validate the new green roof model.
Chapter 6

Experimental Data Analysis

One of the main objectives of this research study was to experimentally quantify heat fluxes around a green roof. This chapter presents data collected in the “Cold Plate” apparatus. Overall, more than 10 experiments were conducted inside the environmental chamber described in Chapter 5. Evapotranspiration, heat flux through substrate, air temperature and incoming long wave radiation were measured with at least two different techniques. Thus, this chapter first compares different techniques used to measure the same physical phenomena and selects a technique for each heat flux that is used for data analyses. Finally, the dynamic behavior of different heat fluxes will be analyzed. Most importantly, the role of evapotranspiration in the heat and mass transfer processed is analyzed.

6.1 Overall Results and Measuring Technique Evaluations

A total of eight experiments with plants and two experiments without plants were successfully conducted. Tables 6-1 and 6-2 show environmental conditions in each of the experiments. Most of the actual environmental conditions were very close to the designed or targeted conditions shown in Tables 6-1 and 6-2. However, solar radiation and air temperatures close to the green roof were the variables most challenging to control. On one hand, solar irradiance at plant height slightly changed from experiment to experiment. On the other hand, there was important air stratification close to the green roof sample because the lamps were a major heat source inside the chamber. These two issues require additional explanations and are discussed in section 6.1.1 and 6.1.2. The driving forces, such as incoming short and long wave
radiation, as well as evapotranspiration and heat flux through the substrate, will be analyzed in sections 8.1.3 to 8.1.5

**Table 6-1:** Summary of environmental conditions for green roof experiments using samples with plants

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Air Temperature above Green Roof Sample (°C)</th>
<th>Return Air Temperature (°C)</th>
<th>Return Air Relative Humidity (%)</th>
<th>Solar Irradiance (W/m²)</th>
<th>Air Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Baseline I</td>
<td>32.3</td>
<td>28.1</td>
<td>31</td>
<td>98</td>
<td>0.12</td>
</tr>
<tr>
<td>2. Humidity</td>
<td>32.2</td>
<td>28.0</td>
<td>46</td>
<td>92</td>
<td>0.11</td>
</tr>
<tr>
<td>3. Solar</td>
<td>31.2</td>
<td>27.9</td>
<td>33</td>
<td>56</td>
<td>0.10</td>
</tr>
<tr>
<td>4. Speed</td>
<td>29.0</td>
<td>28.3</td>
<td>32</td>
<td>84</td>
<td>1.08</td>
</tr>
<tr>
<td>5. Temperature</td>
<td>29.2</td>
<td>26.1</td>
<td>34</td>
<td>71</td>
<td>0.10</td>
</tr>
<tr>
<td>6. Temperature</td>
<td>24.5</td>
<td>23.9</td>
<td>46</td>
<td>65</td>
<td>0.60</td>
</tr>
<tr>
<td>7. Baseline II</td>
<td>31.5</td>
<td>27.7</td>
<td>33</td>
<td>86</td>
<td>0.13</td>
</tr>
<tr>
<td>8. UVA</td>
<td>35.9</td>
<td>32.0</td>
<td>39</td>
<td>158</td>
<td>0.14</td>
</tr>
</tbody>
</table>

**Table 6-2:** Summary of environmental conditions for green roof experiments using samples without plants

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Air Temperature above Green Roof sample (°C)</th>
<th>Return Air Temperature (°C)</th>
<th>Return Air Relative Humidity (%)</th>
<th>Solar Irradiance (W/m²)</th>
<th>Air Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. UVA</td>
<td>37.4</td>
<td>32.60</td>
<td>38</td>
<td>189</td>
<td>0.17</td>
</tr>
<tr>
<td>2. Fluorescent</td>
<td>32.2</td>
<td>28.10</td>
<td>36</td>
<td>107</td>
<td>0.12</td>
</tr>
</tbody>
</table>

**6.1.1 Air Temperature and Humidity**

Air temperature was measured at the return ductwork. Additionally, air temperature above the green roof sample was measured using the hot-sphere anemometers. Hot-sphere anemometers have a temperature sensor located next to the hot-sphere sensor that enables
temperature compensation for air speed measurements. These sensors are coated with reflective aluminum coating. Interestingly, the air temperature measured on the return ductwork and the air temperature measured by the hot-sphere anemometers close to the green roof sample was not the same. The difference between both sensor readings was about 4 °C. This 4 °C difference remained almost constant for all of the experiments with low air speed. However, the temperature difference between the return ductwork measurement and the hot-sphere anemometers measurement decreased to about 1 °C for the high air speed experiments, when the fans were on, as shown in Table 6-1. The 4 °C and 1 °C temperature difference between the return ductwork measurement and the hot-sphere anemometers measurement is mainly due to air being heated between the lamps and the green roof sample. This air heating process is due to the convective heat flux from the lamps and green roof. However, for evapotranspiration and convection calculations, a different air temperature value was used. The air temperature used was equal to the air temperature measured by the anemometers closest to the plants minus 1 °C for the experiments without fans. This subtraction is based on an additional experiment, which used four hot-sphere anemometers and four thermistors measuring air temperature under the lamps, as explained below:

- Two anemometers were used, with the integrated aluminum coating for radiation shielding, along with two thermistors wrapped with only a single layer of aluminum foil.
- The other set of two thermistors and two anemometers were also covered with another layer of aluminum foil.

Sensors with double aluminum protection were on average 1 °C cooler than the sensors with only one layer of aluminum. The 1 °C difference is attributed to the radiation of the lamps heating up the sensors.
In addition, air relative humidity was measured on the return ductwork at the same point where the return air temperature was measured. Thus, the air relative humidity above the plants was calculated using the same humidity ratio obtained from the chamber exhaust reading. This relative humidity calculation assumes that the humidity ratio measured on the return ductwork is the same as it is in the room. This assumption is valid, as it is based on a positive pressurization of the chamber that avoids any humidity infiltrating into the chamber and by the use of high aspiration diffuser that improves mixing of the air. A positive pressure inside the chamber was obtained by having a return air flow rate about 85% of the supply air flow rate in the tightly enclosed chamber.

6.1.2 Incoming Short-wave Radiation

Average short-wave irradiance was measured at the beginning of the experiments in 36 locations at plant level. Figure 6.1 shows the contour map values of irradiance for the setup with UVA lamps. Figure 6-1 also shows the location of thermistors (white circles), heat flux meters (white squares), and central/core area used for experimental analyses (dotted square). The average irradiance at the core area was 160 W/m². The radiation contour map shown in Figure 6-1 also shows relative symmetry in both axes. In addition, the irradiance measured in the core area deviated less than 10% from the peak value.
As explained in Chapter 5, UVA lamps were used for one sample without plants and another with plants. The lights were later replaced by daylight fluorescent lamps because the amount of UVA radiation was damaging the plants. Figure 6-2 and Figure 6-3 show the incoming shortwave radiation contour map for the setup with fluorescent lamps before (October 2008) and after all testing was done (June 2009), respectively. The average irradiance at the core area decreased from 120 W/m² to 70 W/m². This decrease in radiation is due to the decline of the lamps’ natural output with time. The time between the first experiment with the fluorescent lamps (without plants) and the last experiment (Baseline II) was about seven months. The first experiment with fluorescent lamps was performed in October 2008. However, the plant samples were infested with a pest. As a result, tests were delayed until January 2009. During this time, the lamps were still used to keeps the plants healthy.
Figure 6-2. Contour graph of incoming short-wave radiation measured with daylight fluorescent system (October 2008).

Figure 6-3. Contour graph of incoming short-wave radiation measured with daylight fluorescent system (June 2009).

In addition, during all green roof tests, the pyranometer was installed at one side of the green roof samples as shown in Figure 6-3 as a dashed square. The core area average irradiance
fluxes were calculated using recorded values from the square area and using a linear relationship between both initial and final contour map studies. Values are shown in Table 6-1.

6.1.3 Incoming Long-wave Radiation

Long wave radiation was measured with a pyrgeometer and also calculated as explained in Chapter 5. Figure 6-4 shows a contour map for the experiments without fans. The average incoming long wave radiation in the core area is 630 W/m². Likewise, the calculated incoming long wave radiation using lamp and wall temperature is 580 W/m². The average value for the experiment with fans is 560 W/m², while the calculated value is 540 W/m². In both cases, the calculated value based on the simplified 3-surface radiative heat transfer gave good results.

![Incoming Long Wave Radiation Contour Map (W/m²)](image)

Figure 6-4. Incoming long-wave radiation measured with pyrgeometer (June 2009).

6.1.4 Evapotranspiration

As discussed in Chapter 5, evapotranspiration was measured with two different methods: (1) lysimeter (scale) and (2) soil water balance. Figure 6-5 shows the results from both methods
for the Baseline II test. Both methods follow similar day and night variations. However, the evapotranspiration rates from the soil water balance technique tend to have larger values than the rates obtained from the lysimeter during the first couple of days. Overall, the total water losses from the soil water balance method were 10-20% larger than the lysimeter readings. Thus, this study used evapotranspiration rates from the lysimeter because (1) the lysimeter method is the only method that directly measures evapotranspiration, (2) the soil water balance is an indirect and less precise technique, (3) the soil water balance method tends to calculate higher mass losses than those measured by the lysimeter, and (4) the soil water balance method tends to give negative evapotranspiration rates at the beginning of each experiment. This negative evapotranspiration rates would mean that the substrate is gaining weight by condensation. However, careful analysis of dew point temperature inside the chamber showed that all surface temperatures inside the chamber were higher than the dew point temperature. In addition, the scale did not detect any weight gain that will give negative evapotranspiration rates, as shown in Figure 6-5.

![Evapotranspiration Rates Obtained from Lysimeter and Water Balance Methods](image)

Figure 6-5. Evapotranspiration rates obtained from the lysimeter and the soil water balance methods.
6.1.5 Heat Flux through Green Roof

Heat fluxes through green roof substrate were recorded by two different techniques: (1) heat flux meters and (2) heat balance for the “Cold Plate.” Each technique has its tradeoffs. On one hand, the heat flux meter performance depends heavily on good surface contact. Additionally, heat flux meters have a disadvantage of possibly disturbing the temperature field and adding error into the measurements (Goldstein et al. 1998). In contrast, the heat balance method could potentially carry more uncertainties due to additional lateral heat losses on the “Cold Plate” and because it depends on readings from three sensors: (1) supply water thermistor of “Cold Plate,” (2) return water thermistor of “Cold Plate,” and (2) water flow meter of “Cold Plate.” To minimize these uncertainties, “Cold Plate” was heavily insulated around the experimental box (R≈10 m²°C/W or 60 ft² h °F/Btu) and highly accurate water thermistors (accuracy of ±0.1 °C or ±0.2 °C) were used.

Figure 6-6 shows heat flux data from the two different techniques: (1) heat flux meters and (2) heat balance for the “Cold Plate.” Both techniques follow the same day and night trends. However, the heat fluxes calculated with the heat balance across the “Cold Plate” were about 15% larger than the heat fluxes measured by the heat flux meters. The difference between both methods changes from experiment to experiment, as shown in Figure 6-7. Figure 6-7 presents quasi-steady state heat fluxes for all experiments. Overall, heat balance around the “Cold Plate” result in slightly larger heat fluxes. In this study, data from the heat balance method were selected for the analyses because one of the two heat flux meters gave unrealistic readings and the heat balance method calculation represents the total heat flux through the roof.
Figure 6-6. Instantaneous heat fluxes though the green roof sample measured by heat flux meters and heat balance method.

Figure 6-7. Comparison of the quasi-state heat fluxes though green roof sample obtained by heat flux meters and the heat balance for the “Cold Plate.”

All heat fluxes that have two different measuring techniques have been compared.

General conclusions for the method selections are:
• Air temperature was obtained by subtracting 1°C from the hot-sphere anemometer readings for the experiments without fans.

• Air temperature was obtained from the hot-sphere anemometer readings for the experiments with fans.

• Humidity ratio was assumed to be uniform in the entire environmental chamber.

• Evapotranspiration rates were obtained from the lysimeter.

• Heat fluxes through substrate were obtained by the “Cold Plate” heat balance.

• Short-wave radiation fluxes were obtained from the pyranometer readings during experiments.

• Long-wave radiation fluxes were obtained from the pyrgeometer readings.

With these experimental procedures tested and accepted, the next step is to analyze the behavior of heat and mass transfer processes in a green roof sample.

6.2 Data Analysis

This section presents all-important heat fluxes measured, once all the different experimental techniques have been analyzed and compared. The analyzed fluxes are evapotranspiration, conduction, net radiation, and convection. In addition, substrate and plant surface temperature are examined due to their role in the overall heat transfer.

6.2.1 Evapotranspiration

Figure 6-8(a) and Figure 6-8(b) show evapotranspiration rates for experiments using green roof samples with plants and without plants. Experiment numbers are the same as in Table
For the two experiments with green roof samples without plants, the experiment with higher irradiance (UVA) had higher evaporation fluxes. Evaporation in these two experiments was mainly in stage 2, as reviewed in Section 2.3.2. The reason for this is that substrate evaporation is only limited by environmental conditions, such as radiation and air humidity, as well as water content in the substrate and substrate capacity to hold water (Hillel 1998). Thus, as both tests without plants involved the same substrate, the shift in evaporation is mainly due to higher radiation fluxes that produces higher substrate temperatures.

![Graphs showing substrate evaporation vs substrate water content and evapotranspiration vs substrate water content.](image)

Figure 6-8. (a) Evaporation rates for the sample without plants, and (b) evapotranspiration rates for the sample with plants. Error bars represents uncertainty measurements from the scale.

In addition, the sample with plants and without plants behaves differently. Overall the sample with *Delosperma nubigenum* achieved higher evapotranspiration rates than the sample without plants at similar volumetric water content. Figure 6-8(b) shows evapotranspiration rates for the green roof samples with plants. The experiment numbers follow the same order as in Table 6-1 and are summarized below:

1. Baseline I. Conditions equal to San Francisco design conditions. Test lasted 4 days.
2. Humidity. Relative humidity increased up to 50%. Test lasted 4 days.
4. Speed. Wind speed increased to 1 m/s. Test lasted 6 days.
5. Temperature. Air temperature changed to 26 °C. Test lasted 2 days.
6. Temperature. Air temperature changed to 24 °C. Test lasted 2 days.
7. Baseline II. Conditions equal to San Francisco design conditions. Test lasted 6 days.
8. UVA. Solar radiation simulated with UVA lamps. Tested sample have *Sedum spurium*. Test lasted 3 days.

Most of the data in Figure 6-8(b) follow a similar trend except for experiment number 8. The difference is likely because this experiment used different plant species, *Sedum spurium*. Moreover, experiment number 8 used UVA lamps that damaged the plants and probably forced stomata to close. In contrast, experiments number 1 to 7 follow a very similar trend:

- Evapotranspiration rates are high and almost constant up to a volumetric water content of 0.14.
- Evapotranspiration decays linearly with volumetric water content up to 0.07.
- Evapotranspiration rates decrease slower than previous stage in a nonlinear way when volumetric water content is lower than 0.07.

These three evapotranspiration phases can also be observed during day and night variations, as shown in Figures 6-9 (a) and (b). Figures 6-9 (a) and (b) show 10-minute averaged evapotranspiration rates for Baseline II experiment. The gray areas denotes the 10-hour dark period during experiments. As shown in Figure 6-9 (a), the green roof sample achieved the largest and nearly constant evapotranspiration rates during the first two days, or when volumetric water content was above 0.14. Figure 6-9 (a) and (b) show that there is also evapotranspiration during the night. However, day/night evapotranspiration ratio is about 3 when substrate is wet and about 5 when substrate is dry. Larger evapotranspiration during the day is mainly due to the short-wave radiation exciting the plants and warmer leaf temperatures that promote higher vapor pressure.
deficit with the surrounding environment. Finally, data in Figure 6.9 (a) at low substrate water content seems to have “shorter” day or night periods. This visual issue is because the resolution of the water content sensors is not as good as the resolution of the scale.

Figure 6-9. 10-minute averaged evapotranspiration rates for the Baseline II test versus (a) substrate water content and (b) time. Gray areas denote 10-hour dark period.

Figure 6-8 (b) also shows that evapotranspiration rates obtained from experiments number 1 to 3 are very similar. However, experiments number 4 to 7 obtained larger evapotranspiration rates. The first three experiments were conducted in February and early March, while experiments 4 to 7 were conducted in April. This time between experiments 1-3 and 4-7 allowed plants to grow
and increase their LAI, as shown in Figures 6-10 (a) and (b). This proves that plant coverage and LAI have a very important role in evapotranspiration.

Figure 6-10. Photos of the green roof sample (a) before Baseline experiment in February 2009, and (b) before Wind experiment in April 2009.

Among all experiments, experiment number 6 achieved the largest evapotranspiration rates because the wind speed was about 9 times larger than the other values. Thus, larger wind speeds improved convective mass transfer between the plants and the surrounding air. An increase in the wind speed from 0.1 m/s to 1 m/s resulted in an increased evapotranspiration by 10-30%. Moreover, Figure 6-11 shows evapotranspiration for the experiment number 8 with plants versus calculated vapor pressure differential. This relationship is not as strong and clear as with the substrate water content in Figure 6-8 (b); however, Figure 6-12 (a) and (b) show the calculated stomatal resistance using evapotranspiration data and Equation 12 (see section 2.3). There is a relationship between measured evapotranspiration obtained with VPD and substrate water content.
Figure 6-11. Measured evapotranspiration fluxes versus calculated vapor pressure differential for the experiment with green roof samples with plants.

Figure 6-12. Calculated stomatal resistance versus (a) volumetric water content and (b) versus vapor pressure differential. Calculated values come from experimental data and equation (12) multiplied by LAI.

Finally, from all environmental conditions tested, wind speed was the most influential. Humidity, solar radiation, and air temperature did not show strong influences on evapotranspiration. However, future experiments with windy and humid conditions could help to prove whether humidity also has an important role.
In conclusion, from all analyzed variables, the substrate water content was the most important factor in determining the evapotranspiration rates. It is also important to note that Figure 6-8 (b) presents measured evapotranspiration (the combined plant transpiration and substrate evaporation). In contrast, Figure 6-8(a) shows only the bare substrate evaporation or latent heat flux from the substrate. Overall, the plant transpiration or latent heat flux depends on physiological properties of the plants and their stomatal resistance that controls water losses. Therefore, the difference in evapotranspiration rates in Figure 6-8(a) and Figure 6-8(b) is likely due to the plant stomatal resistance to control water losses and additional storage in the plant leaves.

6.2.2 Conductive Heat Flux

Previous research has shown that the thermal conductivity of green roof substrates increases as the water content in the substrate increases, as discussed in section 2.4 (Sailor et al. 2007, Tabares-Velasco and Srebric 2009a). However, heat fluxes through the substrate shown in Figure 6-13 (a) and (b) increase as the substrate gets drier. Lower heat fluxes are due to higher thermal conductivity that allows for higher heat fluxes, but also allows for higher evapotranspiration fluxes. Thus, it appears that the higher evapotranspiration rates overcome the changes in the thermal conductivity. As a result, evapotranspiration plays an important role in diverging heat fluxes from the roof to the environment. A variable albedo or reflectivity may also play a role, as higher albedo values indicate that a smaller amount of incident radiation is being absorbed by the green roof, shown in Figure 2-3. This is an important statement since this could help make informative decision about the tradeoffs between having a wet or dry green roof to further reduce heat fluxes through the roof. Additionally, lower heat fluxes were obtained in the
experiment with the higher wind speed. Finally, lower heat fluxes were obtained in Baseline II test (number 7) compared to Baseline (test 1) despite similar environmental conditions. The decreased fluxes are probably due to the higher LAI, which means higher shading and evapotranspiration diverting and blocking incoming heat gains. This is also consistent with substrate surface temperatures shown in next section along with the calculated substrate thermal conductivity.

6.2.3 Substrate and Plant Surface Temperature

Substrate surface temperatures in Figures 6-14 (a) and (b) show a similar trend to heat fluxes in Figures 6-13 (a) and (b). Green roof samples with plants consistently had lower heat fluxes across the substrate and lower substrate surface temperatures.

Figure 6-13. Measured substrate heat fluxes through (a) the green roof sample without plants, and (b) the green roof sample with plants.
Figure 6-14. Substrate top temperatures for (a) the green roof sample without plants, and (b) the green roof sample with plants

Figure 6-15 shows plant surface temperature. Plant surface temperature is consistently higher than the substrate temperature, because plants are providing shading to the substrate. Plant surface temperature is higher when the substrate is drier, for which evapotranspiration diverts a minimal amount of incoming fluxes. Among all of the experiments, experiment number 7 obtained the lowest surface temperatures due to the improved convection by the wind speed increase. Plant surface temperatures would also be used to calculate the green roof net radiation.

Figure 6-15. Plant surface temperatures for the green roof sample with plants
It is important to mention that plant surface temperatures showed in Figure 6-15 were obtained with thermistors attached to the leaves as explained in section 5.1. Unfortunately, this technique might not measure plant temperature very accurately; despite the thermistors’ accuracy of ±0.2°C. This is because only half the area of the sensor is in contact with the leaf and the other half is exposed to air temperature and incoming radiation. Incoming radiation was minimized by coating the thermistors with aluminum foil. However, to address this weakness in the temperature measurement, an infrared (IR) camera was used during the last day of some experiments to take infrared pictures of the green roof samples. Point to point comparison between the thermistors and IR camera readings showed that the readings from the IR camera were consistently higher by 1-2°C but within the uncertainty of the IR camera of ± 2°C. The same difference was obtained when comparing average plants’ surface temperature obtained from the thermistors and the average temperature obtained from the camera. Moreover, standard deviation of the plants’ surface temperature from small sections was around 0.7-1°C, compared to standard deviation of 1.4-2 °C for the entire green roof area sample. A more complete description is in appendix C.

Figure 6-16 shows measured plant (squares), substrate (circles) surface temperatures and calculated wet bulb temperature (WBT, crosses) for the green roof sample with and without plants. The graph is divided into 9 parts because it is arranged per experimental test. For example, “Soil UVA” has 6 square points that represent the measured values for the experiments without plants and using UVA lamps.
Figure 6-16. Plant (squares), substrate (circles) surface temperatures and calculated wet bulb temperature (WBT, crosses) for the green roof sample without and with plants.

As shown in Figure 6-16, measured plant and substrate temperature were higher than the calculated wet bulb temperature. However, the data shows a tendency to approach the web bulb temperature during the first day of experiments, when the green roof samples were the wettest. Thus, plant and substrate temperature could asymptotically approach wet bulb temperature when the plant surface and substrate top layer are wet.

6.2.4 Substrate Thermal Conductivity

The substrate thermal conductivity of the green roof samples with and without plants was calculated using the heat flux measurements through the substrate and measured temperature difference across the green roof substrate. Figure 6-17 shows the calculated substrate thermal conductivity for all experiments. The dark, continuous line represents the linear regression fitted from about 2/3 of the calculated thermal conductivity, excluding the outliers. Most of the data
follow the linear equation, which is very similar to the one calculated by another field study using a green roof substrate with similar densities (Perino et al. 2003).

![Substrate Thermal Conductivity](image)

Figure 6-17. Calculated substrate thermal conductivity for the green roof sample without and with plants

### 6.2.5 Net Radiation

As reviewed in section 2.2, net radiation represents the difference between the incoming and outgoing short-wave and long-wave radiation at the green roof surface. Thus, net radiation depends on the spectral properties of the green roof, such as reflectivity, but also on the incoming short-wave radiation, temperature of the plants, sky (in this case lamps and surrounding walls) and substrate. Moreover, depending on environmental conditions, net radiation can be positive (incoming fluxes) or negative when there is no short-wave radiation, therefore representing an outgoing flux. Figures 6-18 (a) and (b) shows net radiation for the samples with and without plants. The experiments with UVA lamps obtained higher values possibly because of the higher efficiency and slightly higher power (165W) compared to the daylight fluorescent power (160W).
UVA lamps also contained a special coating that directs most of the radiation downwards, in contrast to the more diffuse radiation of daylight fluorescent lamps. It is also important to mention that measurements of incoming long-wave radiation were not performed with the UVA lighting system. Thus, the values shown here are based on the assumption that the total output (long and short wave radiation) of the UVA and fluorescent lamps should be similar with just a minor correction due to the different input power (165W/160W). Overall, most plant experiments have very similar net radiation, except the experiments with about 50% of lamps being turned off. The largest net radiation was recorded for the wet sample conditions, when plant temperature is the lowest, as shown in Figure 6-15, and the reflectivity is the lowest also, as shown in Figure 2-3. Net radiation decreases as the substrate water content decreases. This is mainly due to the increase in substrate reflectivity and increase in temperature of the plants and substrate. Once the net radiation is known and all other heat fluxes are know, convection is calculated by making an energy balance for the green roof sample.

Figure 6-18. Net (short and long-wave) radiation for (a) the sample without plants, and (b) the sample with plants.
6.2.6 Convective Heat Transfer

Figure 6-19 (a) and (b) show convective heat transfer for the samples without plants and with plants. Convective fluxes are calculated indirectly by subtracting all other measured fluxes from the total measured flux. Thus, convection is the least accurate heat flux measured by the “Cold Plate,” having a calculated accuracy of ±11 W/m². Convective fluxes for the sample with plants are slightly larger than fluxes for the sample without plants. Interestingly, the experiments with the highest wind speed (test 4) have the smallest values of the convective heat transfer rate. This unexpected outcome is due to the increase in wind speed caused by higher evapotranspiration rates and low short-wave radiation compared to outdoor radiation levels. The higher evapotranspiration rates decreased the plant temperature, which consequently decreased convection fluxes. For all cases, convection follows an opposite trend from the evapotranspiration trend. Thus, larger convection fluxes were observed at drier substrate conditions, when the evapotranspiration fluxes are minimal.

![Convective Heat Transfer vs Substrate Water Content](image)

(a) Convective Heat Transfer vs Substrate Water Content

(b) Convective Heat Transfer vs Substrate Water Content

Figure 6-18. Convective heat transfer for (a) the sample without plants, and (b) the sample with plants
6.3 Conclusions

All analyzed heat fluxes are compiled together in Figure 6-19 for the experiments with plants. In Figure 6-19, quasi-steady fluxes discussed in Chapter 6 are plotted versus the time length starting at the beginning of each experiment. All heat fluxes are interconnected and dependent on each other. Among all heat fluxes, the net radiation is the main incoming flux, or driving flux. Net radiation is typically higher during the first days of experiments when the reflectivity is lower and the plant/substrate temperature is the lowest. Evapotranspiration has the role of controlling the intensity of all others fluxes, by modulating or diverting incoming and outgoing heat fluxes depending on plants and environmental conditions. It is also very interesting to observe how convection follows the opposite trend from the evapotranspiration trend. This opposite trend is because convection increases as plant surface temperature increases. This increase in plant temperature also increases the long-wave radiation emitted from the plants, thus also reducing the net radiation. Likewise plant surface temperature increases as evapotranspiration decreases, due to the decrease in the plants ability to convert sensible to latent heat fluxes as the substrate dries. Finally, compared to convection or evapotranspiration, conductive heat fluxes are the least susceptible water content. This is due to the added resistance to heat transfer by the substrate and plants. Thus, most of the incoming heat flux gets diverted out of the green roof. However, the lowest conductive heat fluxes through the green roof were consistently found when the green roof was the wettest. This statement also answers one of the old dilemmas about green roof conduction when the roof is wet and dry as discussed in section 6.2.2. The data shown here proves than lower heat fluxes through the roof are obtained when the green roof is wet. Table 6-3 summarizes all the measured heat fluxes for both green roof samples without plants and with plants. The samples with plants show an average heat flux reduction of
25% compared to samples without plants. In addition, the lowest conductive heat flux occurred at the wettest conditions, with an average reduction of 16% compared to dry conditions.

Table 6-3: Measured energy flux ratios of sensible heat, soil conduction, and latent heat divided by the net radiation in “Cold Plate” green roof experiments

<table>
<thead>
<tr>
<th></th>
<th>Green Roof Sample without Plants (Wet)</th>
<th>Green Roof Sample without Plants (Dry)</th>
<th>Green Roof Sample with Plants (Wet)</th>
<th>Green Roof Sample with Plants (Dry)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{\text{sensible}/R_n}$</td>
<td>0.29</td>
<td>0.40</td>
<td>0.23</td>
<td>0.57</td>
</tr>
<tr>
<td>$Q_{\text{soil}/R_n}$</td>
<td>0.21</td>
<td>0.32</td>
<td>0.09</td>
<td>0.14</td>
</tr>
<tr>
<td>ET/$R_n$</td>
<td>0.50</td>
<td>0.28</td>
<td>0.68</td>
<td>0.29</td>
</tr>
</tbody>
</table>

Figure 6-19 graphically represents the energy balance Equation (1). This figure shows dynamic and complex energetic interactions between plants and the environment. This graph is an achievement that no other previous research work has obtained. Finally, all these data will be used in Chapter 8 to verify and validate the green roof model for energy calculations.
Figure 6-19. Measured heat fluxes for the green roof sample with plants. Time in days represents the days after the experiments started.
Chapter 7

Green Roof Model

Chapter 7 describes the green roof model developed in this research project. This chapter first considers a green roof without plants and then considers a green roof with plants. The green roof model without plants represents the worst case scenario when all plants are dead. The second part of this chapter will then describe the green roof model with plants. Finally, this chapter presents the model for partially exposed green roofs, which is perhaps the most realistic case for a real green roof.

7.1 Green Roof Model without Plants

The scenario of a roof covered with only green roof substrate represents the simplest way to simulate the roof for the worst case scenario when all plant material dies. Energy balance across the roof without plants is similar to Equation (1) in Chapter 2 once the plant metabolic rate is neglected and quasi-steady state conditions are assumed. Under these assumptions, Equation (1) results in the following equation:

\[ R_n = Q_E + Q_{sensible} + Q_{conduction} \]  \hspace{1cm} (22)

Equation (22) can be modified, as shown in Figure 7-1, to have the losses to the surrounding air-sky grouped together in an overall heat loss by means of convection, radiation, and evaporation, as following:
\[ R_{sh,abs} = Q_{film} + Q_{conduction} \]  

(23)

where,

\[ Q_{film} = Q_{convection} + Q_{IR} + Q_{Evaporation} \]

Heat transfer from the substrate to the environment by means of evaporation, convective, and radiative heat transfer.

\[ R_{sh,abs} = \text{Absorbed solar radiation by the green roof substrate} \]

Figure 7-1: Heat fluxes considered in green roof model without plant material.

In Equation (23), absorbed short wave or solar radiation \((R_{sh,abs})\) is calculated using the following equation:

\[ R_{sh,abs} = (1 - \alpha_{soil})R_{sh} \]  

(24)

\(Q_{film}\) represents the heat transfer from the substrate to the environment by means of evaporation, convective heat transfer, and radiative heat transfer. Moreover, by assuming the sky temperature is equal to the air temperature, a film heat transfer coefficient can be calculated.
combining the three resistances in parallel. However, this assumption could underestimate radiative losses during clear sky conditions:

\[ R_{\text{film,sub}} = \frac{R_{\text{conv}}R_{\text{IR}}R_{E}}{R_{\text{conv}} + R_{\text{IR}} + R_{E}} \]  

(25)

where,

- \( R_{\text{conv}} \) = Resistance to convective heat transfer
- \( R_{\text{IR}} \) = Resistance to thermal radiative heat transfer
- \( R_{E} \) = Resistance to latent heat transfer

### 7.1.1 Convection Heat Transfer

The first heat transfer process in Equation (25) is convection. The resistance to convective heat transfer is calculated using Equation (26). Equation (26) combines Equations (9) and (10) for a flat plate into one equation for forced convection (Wang 1982), as following:

\[
N_u = \begin{cases} 
3 + 1.25 \cdot 0.0253 \cdot Re^{0.8} & Gr < 0.068 \cdot Re^{2.2} \quad \text{ForceConvection} \\
2.53 \left( \frac{Gr}{Re^{2.2}} \right)^{1/3} \left( 3 + 1.25 \cdot 0.0253 \cdot Re^{0.8} \right)^{1/3} & 0.068 \cdot Re^{2.2} < Gr < 55.3 \cdot Re^{5/3} \quad \text{MixedConvection} \\
0.15 Ra^{1/3} & 55.3 \cdot Re^{5/3} < Gr \quad \text{NaturalConvection}
\end{cases}
\]

(26)

Equation (26) calculates the Nusselt number for the forced, mixed, and natural convection on a flat surface depending on the ratio of the Grashof number divided by the Reynolds number. The role of wind speed in Equation (26) is embedded in the Reynolds number, because the Reynolds number linearly depends on the wind speed.
7.1.2 Substrate Evaporation

The second resistance in Equation (25) is resistance to evaporation. The resistance to evaporation is defined as the temperature difference between the upper layer of the substrate and the air temperature divided by the substrate evaporation heat flux.

\[ R_E = \frac{T_{\text{top,substrate}} - T_{\text{air}}}{Q_E} \]  \hspace{1cm} (27)

In Equation (27), substrate evaporation is calculated using Equation (20). In this thesis study, a new substrate resistance, \( r_{\text{soil}} \), equation for green roof substrate was developed to properly model substrate evaporation based on the experimental data shown in Chapter 6. The decision to develop a new equation for the substrate resistance to evaporation is based on the fact that none of the existing models for soil evaporation was consistent with our experimental data. It is important to note that the present study had a sophisticated experimental facility, the “Cold Plate” apparatus, for detailed measurements of evapotranspiration rates by the gravimetric method, while simultaneously measuring the total energy balance on the green roof sample (see Chapter 6). Therefore, this important data set provides an opportunity to calibrate the evapotranspiration model specifically for extensive green roofs.

All of the soil evaporation models presented in section 2.3.2 and shown in Figure 2-5 were evaluated using bare soil evaporation data from the “Cold Plate” apparatus. Experimental data, such as substrate water content and soil evaporation, allow for calculation of actual soil resistance when solving for the substrate resistance in Equation (20). A complete analysis of all models is located in Appendix A. In this thesis, the procedure to analyze previous soil...
evaporation models using the experimental data from “Cold Plate” apparatus shown in Chapter 6 was the next step:

1. Analyze alpha (Equation (20)), beta (Equation (20)) and alpha-beta methods (Equation (21)). Following recommendation from a previous study (Mahfouf and Noilhan 1991), these three methods were analyzed in this thesis. Overall, the alpha method resulted in a few negative evaporation values when implemented with the “Cold Plate” data, which is a drawback that has also been reported in the literature (Mahfouf and Noilhan 1991, Ye and Pielke 1993). The beta method performed better than the alpha-beta method when compared with the measured evaporation rates obtained from the “Cold Plate.” Thus, the beta method is implemented into the proposed green roof model.

2. Analyze models using average volumetric water content in the substrate. Once the beta method was selected, the next step was to compare the seven models shown in Figure 2-5 using same average volumetric water content for all models. None of the models performed appropriately. This result is not surprising because most of these models were developed using average volumetric water content for the top 1, 2, and 5 cm layers of the substrate.

3. Develop a new substrate resistance model using half of the experimental data. A new correlation was developed based on six of the twelve days of the experimental data. When compared to the rest of the experimental data, the model performed well except when the substrate was very wet.

4. Analyze models calculating water content profile. This step used measurements of substrate volumetric water content at three different substrate depths: (1) bottom, (2) middle, and (3) diagonal or average values. These three measured values were then used to create a nonlinear volumetric water content profile in the substrate, shown in Appendix A. From these profiles, the average water content for different substrate depths was
calculated. Models then were evaluated with the average water content at the depth for which the models were originally developed. The new equation for green roof substrate performed better than the rest of the models. Another existing model using 5cm of top substrate water content was also fairly consistent with the rest of the results (Bussiere 1985).

The proposed model used to calculate substrate resistance to evaporation is shown in the following equation:

\[
r_{soil} = 34.5 \left( \frac{VWC}{VWC_{sat}} \right)^{3.3}
\]

Equation (28) was developed following previous suggestions that soil evaporation resistance models should include the amount of pores in the substrate, or the porosity (Ye and Pielke 1993, Mahfouf and Noilhan 1991). For that reason, Equation (28) divides volumetric water content by the volumetric water content at saturation to account for the substrate porosity. Equation (28) also follows a power profile that was used by most of the existing soil models (Sun 1982, Bussiere 1985, van de Griend and Owe 1994, Aluwihare and Watyanabe 2003).

### 7.1.3 Long-wave Radiative Heat Flux

Finally, the radiative heat flux between the sky and the substrate and its corresponding resistance to thermal radiative heat transfer for two bodies (one completely surrounding the other) are defined as following (Duffie and Beckman 1991):

\[
Q_{IR} = \varepsilon_{substrate} \sigma (T_{top,substrate}^4 - T_{sky}^4)
\]
There are many models to calculate sky temperature. The simplest approach is to assume sky temperature is equal to air temperature. Other simpler models assume sky temperature is the same to air temperature minus 20°C (Jones 1992) or correlate downward long-wave radiation with air temperature by adding empirical constants (Gaffin et al 2005, Monteith and Unsworth 2008). More complex models are not linear and depend on dew point temperature and time ((Duffie and Beckman, 1992). In this thesis, sky temperature was obtained from the long-wave radiation measured from the pyrgeometer and assuming the room walls and lamps behave like a black body.

7.1.4 Conductive Heat Flux

The conductive heat transfer through the green roof substrate is calculated by Equation (31). The thermal conductivity of the substrate is calculated using the new correlation developed using all data shown in Figure 6-16.

\[ Q_{\text{substrate}} = k_{\text{substrate}} \frac{T_{\text{top,substrate}} - T_{\text{bottom,substrate}}}{L} \]  

\[ k_{\text{substrate}} = 0.37 \times \text{vwc} + 0.17 \]  

7.1.5 Summary of Green Roof Model without Plants

Finally, Table 7-1 summaries all of the recommended equations for the green roof model without plants. The green roof model with plants will then be developed from the model without plants.
Table 7-1: Summary of recommended equations for green roof model without plants

<table>
<thead>
<tr>
<th>Energy Balance</th>
<th>Absorbed Solar Radiation</th>
<th>Convective Heat Transfer</th>
<th>Evaporation Long-wave Radiation</th>
<th>Conduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equation Number</td>
<td>23</td>
<td>24</td>
<td>26</td>
<td>20 and 28</td>
</tr>
</tbody>
</table>

7.2 Green Roof Covered with Plants

As shown in Chapter 6, a green roof covered with plants behaves differently from a green roof without plants. Thus, the green roof model with plants is different from the bare substrate roof model because it includes plants’ shading, plants’ transpiration, and plants’ wind shielding. This model is an extension of the model for green roof without plants, and therefore the new thermal circuit incorporates these plant-related heat transfer phenomena as shown in Figure 7-2.

Figure 7-2: Heat fluxes considered in green roof model that includes plant material.
Based on Figure 7-2, and assuming negligible thermal storage and metabolic rate, the energy balance for the plant canopy and for the substrate underneath the plants is given by the following two equations, respectively:

\[ R_{sh,abs,plants} = Q_{film,plants} + Q_{IR} \]  
\[ R_{sh,abs,substrate} = -Q_{IR} + Q_s + Q_{substrate} + Q_{IR,sky} + Q_E \]

where,

- \( R_{sh,abs,plants} \) = absorbed short wave or solar radiation by the plants
- \( Q_{film,plants} = Q_{S,S} + Q_{IR} + Q_T \) = heat transfer between plants and the surrounding environment by means of latent (transpiration), convective and radiative heat transfer
- \( Q_{IR} \) = radiative heat transfer between the plant layer and the top substrate layer
- \( Q_{S,S} \) = convective heat transfer between the top substrate layer and the surrounding air
- \( R_{sh,abs,substrate} \) = absorbed solar radiation by substrate underneath the plants
- \( Q_{substrate} \) = conductive heat flux through green roof substrate
- \( Q_{IR,substrate,sky} \) = thermal radiation or radiative heat exchange between substrate and sky

### 7.2.1 Absorbed Short and Long wave Radiation

Not only does solar radiation play an important role in the heat and mass transfer, but it also represents the major incoming flux in Equations (33) and (34) when the sun is at its higher position in the sky. The amount of solar radiation absorbed by the plants and substrate underneath the plants depends on the spectral properties of both surfaces, as well as the vegetation density in terms of LAI. Absorbed solar radiation by the plants is calculated using the following equation:

\[ R_{sh,abs,plants} = \left( 1 - \alpha_{plants} - \tau_{plants,solar} \right) \left( 1 + \tau_{plants} \alpha_{substrate} \right) R_{sh} \]
In Equation (35) absorbed or intercepted solar radiation by the plants will change as the incident radiation changes hourly and daily. Moreover, the amount of intercepted solar radiation depends on the transmissivity of the plant layer which in turn depends on the solar altitude and leaf orientation as reviewed in Table 2-3. For horizontal flat leaves, the transmissivity remains constant. Likewise, absorbed solar radiation covered for the substrate underneath the plants represents the amount of radiation that is not intercepted by the leaves, transmitted or reflected to the substrate. In this study, absorbed solar radiation is calculated using the following equation:

\[ R_{sh,abs,plants} = \tau_{plants,solar} \left( 1 - \alpha_{substrate} \right) R_{sh} \]  

(36)

\( \tau_{plants,solar} \) is the transmittance for shortwave radiation as expressed in Equation (4) in Chapter 2. After solar radiation, thermal radiation between the sky, plants, and green roof substrate can play an important role, especially when the sky is clear. In this model, thermal radiation is calculated using the following two equations:

\[ Q_{IR,plants,sky} = \left( I - \tau_{plants,IR} \right) e_{plants} \sigma \left( T_{plants}^4 - T_{sky}^4 \right) \]  

(37)

\[ Q_{IR,substrate,conv,sky} = \tau_{plants,IR} e_{substrate} \sigma \left( T_{plants}^4 - T_{sky}^4 \right) \]  

(38)

The transmittance for thermal radiation, \( \tau_{plants,IR} \), stands for the radiation that will not be intercepted by any leaves. \( \tau_{plants,IR} \) is calculated the same way as \( \tau_{plants,solar} \), only using a different extinction coefficient as explained in Chapter 2.

**7.2.2 Long-wave Radiation between Plants and Substrate**

Radiation exchange between the plant canopy and top substrate is very complex and difficult to calculate. However, several assumptions can be made to simplify the calculations. The most
common assumption used in green roof modeling, borrowed from the meteorological mesoscale models, is to represent plants and substrate as two flat plates/surfaces. This assumption is not necessarily valid for large trees, but it is fairly realistic for low stature plants, which tremendously simplifies the calculation. Overall, the radiative heat exchange can be calculated using the following three assumptions (Duffie and Beckman 1991):

1. Two parallel surfaces with different areas,
2. Two infinite parallel plates/surfaces, and
3. Small area (substrate) surrounded by a large enclosure (plants).

Most of the green roof models have used assumption 3 (Palomo del Barrio 1998, Alexandri and Jones 2007) or assumption 2 (Sailor 2008). However, assumption 1 represents the conditions that are most realistic, as the total surface area of the leaves is higher than the substrate surfaces for higher LAI. Thus, this study initially applied assumption 1 in Equation (39).

\[ Q_{IR} = \left( 1 - \tau_{IR} \right) \frac{\sigma(T_{plants} - T_{top,substrate})}{I - \varepsilon_{substrate} - \varepsilon_{plants} \cdot LAI} \]

From the three approaches, assumption 1 requires the most information, as one must determine the view factor that depends on LAI as well as plant height (Incropera and DeWitt 1996). To select a model for thermal radiation, the three modes were tested using LAI and surface temperature values from the “Cold Plate” apparatus. The results from the three approaches differed less than 10%, or less than 4W/m². The reason for similar values between the three approaches is probably due to the similar emissivity values of the substrate and plants, which are close to 1. From the three assumptions, the model with assumption 1 consistently obtained the lowest value, followed by the model with assumption 2. As a result, this study will use assumption 2 because the added simplicity does not compromise the accuracy of the calculations.
7.2.3 Convective Heat Transfer

The next heat transfer mechanism to be considered is convection. The convective heat transfer coefficient is calculated using Equation (26), originally developed for horizontal flat plates. Thus, this study has added a coefficient to account for the roughness of the plants. The coefficient is based on previous research for convection heat transfer of plant leaves (Schuepp 1993). In contrast, substrate convective heat transfer is calculated using an equation developed for convection for porous media (Bejan 2004), assuming the air speed in the porous media is 1/3 of the air speed above the plants (Deardoff 1978).

\[
Q_{\text{conv, plants}} = 1.5 \cdot \text{LAI} \cdot h_{\text{conv}} (T_{\text{plants}} - T_{\text{air}}) \quad (41)
\]

\[
Q_{\text{conv, substrate, conv}} = h_{\text{sub}} (T_{\text{substrate, top}} - T_{\text{air}}) \quad (42)
\]

where,

\[
h_{\text{sub}} = \frac{h_{\text{por}} \cdot h_{\text{conv}}}{h_{\text{por}} + h_{\text{conv}}} \], substrate convective heat transfer coefficient

\[
\text{Nu}_{\text{por}} = 1.128 \cdot \text{Pe}^{0.5} \], Nusselt number for porous media (Bejan 2004)

\[
\text{Pe} = 0.3V_{\text{air}} \cdot \frac{\text{Length}}{\alpha_{\text{por}}} \], Péclet number (Deardoff 1978, Bejan 2004)

\[
k_{\text{por}} = \phi \cdot k_{\text{air}} + (1 - \phi) \cdot k_{\text{plants}} \], thermal conductivity of porous media (Bejan 2004)

\[
k_{\text{plants}} = 0.50 \], thermal conductivity of leaves (Hays 1975)

\[
\phi = 0.85 \], porosity calculated of plant layer from LAI measurement.

7.2.4 Evapotranspiration

The next heat flux shown in the energy balances in Equation (30) and Equation (31) are substrate evaporation and plant transpiration. Substrate evaporation is calculated using Equation
(20), Equation (28), and modeling the plants as porous media. Likewise, plant transpiration is calculated using Equation (12) and the multiplicative approach proposed by Jarvis (Jarvis 1976), as followed by most recent green roof and SVAT models:

\[
\frac{r_{\text{plants}}}{LAI} = \frac{r_{\text{stomatal}_{\text{min}}}}{LAI} \cdot f_{\text{solar}} \cdot f_{\text{VPD}} \cdot f_{\text{vwc}} \cdot f_{\text{Temperature}} \tag{43}
\]

Each of the empirical functions “f” in Equation (41) represents a role that each environmental and plant variable, such as solar radiation, VPD, and water content, plays in transpiration. Different functions were collected from several published SVAT or green roof models (Jarvis 1976, Deordoff 1978, Dickinson 1984, Stahghellini 1987, Stewart 1988, Jacquemin and Noilhan 1990, Avissar and Pielke 1991, Dolman 1993, Oren et al. 1999, Pielke 2002, van de Hurk et al. 2000, Ogle and Reynolds 2002). These functions were developed in different environmental conditions and from different plant types, such as tropical trees or desert shrubs. However, no previous study has evaluated whether these functions are valid in a green roof environment. The functions shown in Figures 2-4 to 2-6 in Chapter 2 were evaluated and compared with experimental data to assess the impact solar radiation, substrate water content, VPD, and temperature have in plant transpiration. The total number of functions evaluated is:

1. 9 functions for solar radiation,
2. 8 functions for water content,
3. 6 functions for VPD, and
4. 2 functions for temperature.

Equations (12) and (13) in Chapter 2 were used to calculate plants resistance and to compare stomatal values based on Equation (12) and Equation (13) (Penman-Monteith). In this evaluation, 12 quasi-state steady green roof data sets were used (6 with low speed and 6 with high speed). The steps followed to calculate each term in Equation (41) are:
1. Minimum stomatal resistance calculation. The value of $r_{\text{plants}}$ for the data set with the highest volumetric water content was used to calculate minimal stomatal resistance when evapotranspiration was the highest. The calculated values, 500-700 s/m, are within the expected range for succulent plants.

2. Analysis of all functions for stomatal resistance. 19 different combinations of plant stomatal models were tested. Not all possible combinations of functions were analyzed because a few functions showed different trends when compared to the experimental data.

3. Selection of the best stomatal model. The models that performed the best are compared in Figure 7-3. The continuous line in Figure 7-3 represents perfect matching. The best model incorporates a sub-component for VPD that was empirically developed from desert plants. The model selected is Desert 3 (D-3). There is another stomatal model ($r_6$) that provided similar performance to Desert 3. However, the Desert 3 model was selected because $r_6$ tends to overestimate minimum stomatal resistances. Overall, the model performed well, but tends to overestimate stomatal resistance when the substrate has high volumetric water content.
Figure 7-3: Calculated stomatal resistance from laboratory experiments using Equation (12) versus calculated stomatal resistance from different models with closer agreement to experimentally calculated stomatal resistance. Continuous line represents perfect matching.

The functions selected to calculate stomatal resistance are:

\[
f_{\text{solar}} = 1 + e^{-0.634(R_s - 3.5)}
\]

\[
f_{VWC} = \begin{cases} 
1 & \text{VWC} > 0.7VWC_{fc} \\
\frac{VWC_{fc} - VWC_{wp}}{VWC - VWC_{wp}} & \text{VWC}_{wp} < \text{VWC} < 0.7VWC_{fc} \\
\frac{1000}{VWC_{wp}} & \text{VWC}_{wp} > \text{VWC}
\end{cases}
\]

\[
f_{VPD} = \frac{1}{1 - 0.41\ln(\varepsilon_{x,\text{plants}} - \varepsilon_a)}
\]

\[
f_{\text{temp}} = \frac{1}{1 - 0.0016(30 - (T_{\text{plants}} - 273.15)^2)}
\]

### 7.2.5 Summary of Green Roof Model with Plants

Finally, Table 7-2 summaries all of the recommended equations for the green roof model with plants. The green roof model with plants is an extension of the model without plants.
Table 7-2: Summary of recommended equations for green roof model with plants

<table>
<thead>
<tr>
<th></th>
<th>Energy Balance</th>
<th>Absorbed Solar Radiation</th>
<th>Long wave Radiation</th>
<th>IR Plants Substrate</th>
<th>Convective Heat Transfer</th>
<th>Evaporation</th>
<th>Conduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant</td>
<td>33</td>
<td>35</td>
<td>37</td>
<td>40</td>
<td>41</td>
<td>12,43-47</td>
<td>N/A</td>
</tr>
<tr>
<td>Substrate</td>
<td>34</td>
<td>36</td>
<td>38</td>
<td>40</td>
<td>42</td>
<td>20,28</td>
<td>31 and 32</td>
</tr>
</tbody>
</table>

7.3 Green Roof Partially Covered with Plants

Most of the green roof models have assumed that the plants are healthy and fully covering the roof. However, this assumption may be far from reality. Thus, a robust green roof model should also consider the plant coverage ($\sigma_f$) of the green roof. Assuming a parallel circuit between a roof covered by plants and bare substrate roof, the heat transfer through the roof and the total evapotranspiration can be calculated by:

$$Q_{\text{substrate}} = \sigma_f Q_{\text{substrate, covered}} + (1 - \sigma_f) Q_{\text{substrate, bare}} \quad (48)$$

$$Q_{\text{ET,total}} = \sigma_f (Q_{E,\text{substrate,cov}} + Q_{T,\text{plants}}) + (1 - \sigma_f) Q_{E,\text{substrate,bare}} \quad (49)$$

In conclusion, for a green roof that is only partially covered, the model for a green roof with plants and without plants should be evaluated simultaneously to calculate the total heat flux to the roof.

7.4 Conclusions

A new green roof model is proposed. The model considers heat and mass transfer processes between the sky, plants, and substrate. Based on laboratory experimental data collected in the “Cold Plate” apparatus, a new substrate resistance to soil evaporation is introduced.
Moreover, previous functions of plant resistance are evaluated and the functions that best approximate the measured values are selected. These two steps are important for correct evapotranspiration calculations and have not been done previously. For full implementation into a building energy simulation code, a model should be fully verified and validated. Chapter 8 will assess the performance of the model in steady-state conditions using our additional experimental data.
Chapter 8

Model Verification and Validation

The next step after a model is developed is verification and validation. Verification and validation are procedures that properly assess whether a model is correctly simulating the actual physical phenomena of a system. Thus, verification and validation is performed using the data presented in Chapter 6 and the model described in Chapter 7.

8.1 Verification of Individual Heat Transfer Processes

The definition of verification varies according to the field of study. For example, the American Institute of Aeronautics and Astronautics (AIAA) defines verification as “the process of determining that a (physical/mathematical) model implementation accurately represents the developer’s conceptual description of the model and the solution on the model” (AIAA 1998). ASHRAE describes verification as a process that “identifies relevant physical phenomena for analysis and provides instructions on how to assess whether a particular CFD code can account for those physical phenomena” (ASHRAE 2005). A broader definition is used by the European Research Community on Flow, Turbulence and Combustion (ERCOFTAC) that defines verification as “procedure to ensure that the program solves the equations correctly” (ERCOFTAC 2000).

In this thesis, verification would be understood as a process to evaluate the ability of the model components to simulate a specific physical phenomenon. Thus, this section would evaluate
the performance of specific components of the model where experimental data is available. This
is not calibration or evaluation, because the components would not be changed or tune after the
verification is done. In contrast, this procedure will show how the chosen or developed
component works when compared with experimental data. The components analyze in this
section are: (1) convective heat transfer, (2) evapotranspiration and (3) conduction through green
roof substrate. The objective of this verification process is to understand the capabilities of each
of these three model components to predict the heat and mass transfer interactions between plants
and the surrounding environment. The three fluxes will be analyzed separately in sections 8.1.1 to
8.1.3. Data used for the verification were obtained from experiments without plants (Soil UVA
and Soil Day) and from experiments 1 to 8 (Baseline, Humidity, Solar, Wind, Temp and Base II,
UVA plants).

8.1.1 Convective Heat Flux

The convective heat flux will first be analyzed as it is also interrelated to the ability of the
surrounding air to transport water vapor from the plants. The input variables for convective heat
transfer are: (1) substrate surface temperature, (2) plant surface temperature, (3) air temperature,
(4) air velocity, (5) LAI, and (6) characteristic length of the green roof sample. From these 6
inputs, substrate and plant surface temperature would not be provided when the full model is
implemented, as they will be calculated by the green roof model. In addition, as explained in
Chapter 5, LAI was manually measured for the green roof sample with Delosperma nubigenum
about a month and half later after all the described experiments were performed. This task was
performed after all experiments were done because, even tough is not completely destructive task,
there is significant damage to the plants while counting each leaf. The calculated LAI value is
2.7. However, a smaller LAI was used in model verification process depending on the date the
experiment was performed because the plants were growing during each test. For the sample with *Sedum spurium*, the value calculated from the NDVI equation was used because the calculated LAI agreed with the FAO equation as well (Allen et al. 1998) as explain in Chapter 5.

- LAI was equal to 2 for experiments 1-3 and 8 (Baseline, Humidity, Solar, and UVA)
- LAI was equal to 2.3 for experiments 4-7 (Wind, Temp I, Temp II, and Base II)

Figure 8-1 shows measured (squares) and calculated (circles) convective heat transfer. The graph is divided in 9 parts because it is arranged per experimental test. For example, “Soil UVA” has 6 square points that represent the measured values for the experiments without plants and using UVA lamps. In the same way, “Base” represents experiment 1 or the baseline benchmark. Additionally, the x-axis represents counter of all the experimental days involved. The remaining experiments follow the same notation as explained in Table 5-1 and Table 6-1.

Overall, the convective model component is able to predict a similar trend to the experimental data with a root mean square error (RMSE) of 23.6 W/m² for experiments without plants and 26.3 W/m² for the experiments with plants. However, the model consistently under predicts the convective heat transfer. The highest discrepancies between measurements and convective model component are during the first day of experiments. Thus, the discrepancies are due to the low temperature difference between the plants and surrounding air. Importantly, these convective model discrepancies will also affect evapotranspiration, because of the similarity between the convective heat and mass transfer used in the model. Finally the probability plots of the normalize bias ([data-model]/data) in Appendix D show that the normalize bias does not follow a normal distribution, as there are a few points were the model underestimates convection.
8.1.2 Evapotranspiration

As discussed in Chapter 6, evapotranspiration has an important role by redirecting incoming heat fluxes off the roof. Thus, it is very important to correctly simulate this phenomenon. Figure 8-2 shows measured (squares) and calculated (circles) evapotranspiration, following the same notation as in Figure 8-1. The input variables for calculating evapotranspiration are: (1) substrate surface temperature, (2) plant surface temperature, (3) air temperature, (4) air velocity, (5) air relative humidity, (6) LAI, (7) substrate water content, and (8) characteristic length of the green roof sample. Calculated evapotranspiration fluxes are based on the green roof model described in Chapter 7.
Figure 8-2: Measured (squares) and calculated (circles) evapotranspiration fluxes.

The evapotranspiration model component was able to reproduce the measured evapotranspiration fluxes. This is an expected, but still encouraging, result as the stomatal function was selected using some of the experimental points as described in Chapter 7. However, the experimental conditions in Figure 8-2 are different from the conditions used in Chapter 7. Thus, this proves that the model is able to predict evapotranspiration under different environmental conditions. However, substrate evaporation component tend to overestimate evaporation at higher substrate water contents. As with the convective model component, the evapotranspiration model fluxes did not agree with the data from experiment with different air temperatures by 30-40%. Overall the evapotranspiration component had a similar root mean square error as the convection component. The root mean square error is 21.0 W/m² for experiments without plants and 23.3 W/m² for the experiments with plants. Nevertheless, the normalized bias follows a normal distribution as shown in appendix D.

In addition, most of the cases with good agreement between measured and calculated convective heat transfer also agree with measured and calculated evapotranspiration. Likewise, in
the wind experiment, the model underestimation of convection during the first two days of experiments, gave also an underestimation of evapotranspiration during the first couple of days. The underestimation of evapotranspiration is probably due to the model deficiencies in predicting the turbulent transport phenomena between the plants and the surrounding air. This is particularly important when the substrate is wet, because the plant and/or substrate resistance is small and similar to the aerodynamic resistance of the surrounding air. Thus, future studies can focus on studying convective heat transfer at plant material because this topic was beyond the scope of this thesis.

8.1.3 Heat Flux through Green Roof Substrate

The conduction through the green roof substrate is ultimately the most important parameter to calculate from a building energy use perspective. Conduction ultimately depends on the temperature difference across the substrate and the thermal conductivity. Therefore, the input variables for calculating substrate heat flux are: (1) substrate top surface temperature, (2) substrate bottom surface temperature, (3) substrate water conductivity, and (4) substrate depth. Figure 8-2 shows measured (squares) and calculated (circles) conduction heat fluxes through the green roof substrate. For most of the cases, the thermal conductivity model component gives a good agreement with the measured heat fluxes. The root mean square error is 2.1 W/m² for experiments without plants and 4.3 W/m² for the experiments with plants. The good performance and lower root mean square errors are somehow expected, as the thermal conductivity model was developed using subset of data collected in “Cold Plate” apparatus (see section 6.2.4). However, it is important to analyze how each component works and behave in different environmental conditions, including a substrate with plant roots and without plant roots that could potential change the thermal conductivity.
8.1.4 Conclusions from Verification of Individual Heat Transfer Processes

Three components of the green roof model were verified to assure they represent the actual physical phenomena. The components evaluated are: (1) convection, (2) evapotranspiration and (3) heat flux through the substrate. Overall the three components performed well. Table 8-1 shows their root mean square errors. Among the three components, the convective heat transfer component shows the largest discrepancies when compared with the experimental data. It is worth mentioning that convective heat transfer was not measured directly, thus the uncertainties related to convection is relatively high compared to the other measured variables. However, the main reason for the disagreement between the convective model component and measured data is probably because the model uses an equation derived for convective heat transfer over a flat plate. As described in section 2.4, experiments with leaves have shown that the green roof surface does not behave as a flat plate. Future research using the experimental data could develop a new empirical equation for convective heat transfer for low stature plants. Finally, now that the
performances of these three important components are well known, the study can proceed with a full validation of the model.

**Table 8-1**: Root mean square error of model components in verification process

<table>
<thead>
<tr>
<th></th>
<th>Green Roof Experiments without Plants</th>
<th>Green Roof Experiments with Plants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evapotranspiration</td>
<td>21</td>
<td>23.3</td>
</tr>
<tr>
<td>(W/m²)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Convection (W/m²)</td>
<td>23.6</td>
<td>26.3</td>
</tr>
<tr>
<td>Conduction (W/m²)</td>
<td>2.1</td>
<td>4.3</td>
</tr>
</tbody>
</table>

**8.2 Laboratory Steady State Validation**

After the components have been verified, the next step is model validation. This next step has previous knowledge about the limitations of each green roof model component. As with verification, there are several definitions for validation. The chosen one for this thesis is closed to the definition of ERCOFTAC that defines validation as a “procedure to test the extent to which the model accurately represents reality” (ERCOFTAC 2000). Thus, in this thesis, the validation would be the procedure to demonstrate that the model can calculate an actual green roof performance. The validation will consist of all of the experiments performed in the chamber in quasi-steady state conditions. However, for validating purposes the model required inputs are less than the inputs used in the verification process. The inputs required for validation are:

- air temperature,
- air relative humidity,
- air speed,
- sky temperature,
- incoming solar radiation,
- substrate water content,
• LAI, and
• bottom substrate temperature.

The bottom surface substrate temperature is the boundary condition used as an input in the current version of the green roof model. The sky temperature was calculated from the pyrgeometer data. The sky temperature value was between the surrounding air and the lamps’ temperature. Once all the data are inputted in the model, the variables to analyze are: (1) evapotranspiration, (2) convection, (3) conduction, (4) substrate temperature, (5) plant surface temperature, and (6) net radiation.

In addition, radiation from the fluorescent lamps was assumed to be diffuse and not direct. Thus, the sample with Delosperma was conceptualized by assuming that the leaves have a conical leaf angle distribution (see Table 2-3). The sample with Sedum was conceptualized by assuming that the leaves have a horizontal leaf angle distribution (see Table 2-3). Overall, the calculated canopy transmittance values $\tau_d$ for diffuse radiation are less than 20% for the samples with plants, which agrees with the data from another study shown in Table 2-2 in Chapter 2.

8.2.1 Evapotranspiration

Figure 8-4 shows measured (squares) and calculated (circles) evapotranspiration fluxes. Data from experiments without plants only represents substrate evaporation because these two tests did not have any plant material. On one hand, the model without plants works well, except during first couple of days when it over predicts evaporation flux. On the other hand, the model with plants also works well. The model follows the same trend as the experimental data, but under predicts evapotranspiration when samples are the wettest. Figure 8-4 shows similar results as in the verification process, with a normalized error following a normal distribution and RMSE
of 21.4 W/m² (without plants) and 23 W/m² (with plants). This is a good sign as it means that the plant and substrate temperature are well predicted.

Figure 8-4: Measured (squares) and calculated (circles) evapotranspiration fluxes.

8.2.2 Convective Heat Flux

Figure 8-4 shows measured (squares) and calculated (circles) evapotranspiration fluxes. As discussed in previous chapters, evapotranspiration and convection are strongly interrelated. Thus, the performance of the model shown in Figure 8-5 is similar to the one observed in the verification process. Overall the normalized error follows a normal distribution and has a RMSE equal to 17.0 W/m² (without plants) and 18.0 W/m² (with plants).
8.2.3 Heat Flux through Green Roof Substrate

Figure 8-6 shows measured (squares) and calculated (circles) conduction heat fluxes. The model predicts lower heat flux reduction for green roof samples with plants than with a green roof sample without plants. Overall, the model’s normalized error follows a normal distribution and has a RMSE equal to 4.4 W/m² (without plants) and 4.0 W/m² (with plants). However, the model tends to overestimate heat fluxes in some cases. The case with higher wind speed shows that the model output follows a different trend than the trend observed with experimental data. This result is probably due to the model underestimation of evapotranspiration during the first two days, the same time when the model overestimates heat flux though the substrate. The same problem occurs with the experiments using higher humidity levels. Thus, this proves how important is to estimate each of the different heat and mass transfer processes. Finally, the heat flux through the roof is directly proportional to the temperature difference between the top and bottom of the substrate. Thus, these two temperatures will be analyzed in more details.

Figure 8-5: Measured (squares) and calculated (circles) convective heat transfer.
8.2.3.1 Substrate Surface Temperature

Figure 8-7 shows measured (squares) and calculated (circles) substrate surface temperatures. Data from the experiments without plants represent the bare substrate temperature. In contrast, the data from the experiments with plants represents the temperature of the substrate covered by the plants. The model predicts the shading of the plants, but tends to overestimate the temperature of the substrate underneath the plants. The reason for the over prediction of substrate temperature could potentially be due to under prediction of the shading or soil evaporation. Another reason could be the albedo of the substrate, because no spectral reflectivity test was performed for the sample without plants. However, substrate also interacts with the plants by radiative heat transfer. Thus, the plants surface temperature will be analyzed in more details. Overall the model’s normalized error follows a normal distribution and has a RMSE equal to 1.8 °C (without plants) and 2.0 °C (with plants).
8.2.3.2 Plant Surface Temperature

Figure 8-8 shows measured (squares) and calculated (circles) plant surface temperatures. For this specific variable, there is no available data for the green roof samples without plants. Model predictions are generally good, with exception of the first couple of days. This trend has been consistent for all the of heat transfer processes. Overall the model’s normalized error follows a normal distribution and has a RMSE equal to 1.9 °C.
Figure 8-8: Measured (squares) and calculated (circles) surface plant temperatures.

8.2.4 Net Radiation

Finally, Figure 8-9 shows measured (squares) and calculated (circles) net radiation. Net radiation is a very important parameter as it represents the major incoming flux. For most cases, the model calculated a very similar net radiation to the experimental data. For the cases where the model overestimate surface temperature (soil or plants), the net radiation is under predicted. This connection between surface temperature and net radiation is because net radiation depends strongly on the surface temperature as show in Chapter 2.1. Thus, when the surface temperature is well predicted, net radiation is well predicted too. In addition, the calculated net radiation for the experiment “Soil UVA” underestimates net radiation. In contrast, the calculated net radiation for the experiment “Soil Day” agrees well. This difference between both experiments could be attributable to the spectral reflectivity of the substrate, because each experiment has a different par of the solar spectrum.
8.3 Conclusions

A new green roof model is validated using quasi-steady state experimental data. To our best knowledge, this is the first study that performs this type of rigorous validation approach. It is important to point out that none of the current green roof models have performed this type of validation. Consequently, it is not possible to assess how well they perform with respect to individual heat flux components. In this thesis, the performance of the new green roof model during validation is analyzed in Table 8-2 based on normalized bias ([data-model]/data), root mean square error (RMSE), and normalized root mean square error (NRMSE). This validation show the model tends to predict most of the heat and mass transfer appropriately, but also tends to underestimate maximum evapotranspiration rates. Further research on convective heat transfer for plants is recommended as well as a spectral reflectivity measurement of the substrate to improve the accuracy of the model.
Table 8-2: Green roof model performance based on calculated normalized bias, root mean square error (RMSE), and normalized root mean square error (NRMSE) during validation.

<table>
<thead>
<tr>
<th></th>
<th>Green Roof Experiments without Plants</th>
<th>Green Roof Experiments with Plants</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normalize bias</td>
<td>RMSE (W/m²)</td>
</tr>
<tr>
<td>Evapotranspiration (W/m²)</td>
<td>-0.24</td>
<td>21.4 W/m²</td>
</tr>
<tr>
<td>Convection (W/m²)</td>
<td>-0.16</td>
<td>17.0 W/m²</td>
</tr>
<tr>
<td>Conduction (W/m²)</td>
<td>-0.14</td>
<td>4.4 W/m²</td>
</tr>
<tr>
<td>Substrate Temperature (°C)</td>
<td>-0.06</td>
<td>1.8°C</td>
</tr>
<tr>
<td>Plant Temperature (°C)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Chapter 9

Conclusions and Future Work

This research project had the objectives of (1) experimentally quantifying all of the important heat and mass transfer phenomena, and (2) developing a new heat and mass transfer green roof model. To meet the first objective, a new apparatus, the “Cold Plate,” was designed and built inside an environmental chamber to measure all important heat and mass transfer in a controlled environment. Subsequently, a new green roof model was developed, which was the second objective. The model used the experimental data obtained from the “Cold Plate” to evaluate different evapotranspiration models. Data obtained from these experiments was analyzed and used for model validation.

9.1 Conclusions from Experimental Analysis

As reviewed in section 4.1 previous field, laboratory, and numerical studies have proven that green roofs can decrease the heat flux through the roof by 18-75%. This large variation of heat flux reduction depends on several factors such as weather, roof design and roof insulation. Energy flux reduction is more significant in roofs that are not strongly insulated. The more the insulation already installed on a roof (meeting ASHRAE Standard. 90.1), the lower the thermal benefits from the green roof. Therefore, there could be scenarios where, from an energy building consumption point of view, a green roof would not offer any significant benefit. However, green roofs offer other benefits as discussed in section 1.2 such as storm water management that add value to this technology. Thus, the decision to install a green roof should be based on several factors such as cost, heat flux reduction, roof membrane lifetime and storm water management.
Although there have been numerous studies studying green roofs, to the best of our knowledge, there is no single study that has measured all of the important heat and mass transfer processes simultaneously. This presents a challenging task that is essential to completely develop and validate a green roof heat transfer model.

To undertake this task, the “Cold Plate” apparatus was developed; it is a new kind of apparatus that measures all of the important heat fluxes observed in the quasi-steady state heat and mass transfer analyses for a green roof. Experiments were conducted in a full-scale environmental chamber that simulated outdoor conditions. Currently, there is no other experimental apparatus that simultaneously measures the same physical phenomena. 10 different experiments were conducted inside the chamber, as described in Chapter 6.

The data obtained from these experiments show that plants make a significant contribution to the reduction of heat flux through the roof by means of shading, wind shielding, and most importantly, efficiently controlling their water losses. These conclusions were obtained after comparing data from experiments with green roof samples with and without plants. Overall, the samples with plants achieved significantly lower heat fluxes through the green roof substrate. Additionally, careful analysis of the data has shown that the lowest energy fluxes through the substrate were achieved when green roof samples had the highest water content. Thus, it appears that the higher evapotranspiration rates overcome the changes in the thermal conductivity. As a result, evapotranspiration plays an important role in diverging heat fluxes from the roof to the environment.
Data from the experiments also show that all heat fluxes are interconnected and dependent on each other. Among all heat fluxes, the net radiation is the main incoming flux, or driving flux. Evapotranspiration has the role of controlling the intensity of all others fluxes by modulating or diverting incoming and outgoing heat fluxes depending on plants and environmental conditions.

9.2 New Heat and Mass Transfer Green Roof Model

A new green roof model was proposed and validated using quasi-steady state experimental data. The model considers heat and mass transfer processes between the sky, plants, and substrate. Additionally, a new substrate resistance to soil evaporation was introduced based on laboratory experimental data collected in the “Cold Plate” apparatus. Likewise, a new set of stomatal resistance functions were selected based on previous stomatal functions that best approximate the measured values. To our knowledge, this is the first study that has performed this type of rigorous approach. The validation shows that the model tends to predict most of the heat and mass transfer appropriately, but it tends to underestimate maximal evapotranspiration.

9.3 Future Work

One of the long term goals of this research is to be able to predict the building energy savings when a green roof is installed. The present research made significant progress to this end by being the first study that simultaneously measured all important heat and mass fluxes inside an environmental chamber. Data from these experiments have brought new results that show that plants do have an important role in the heat and mass transfer phenomena. Furthermore, as explained in section 9.1 and section 9.2, a new steady-state model was validated. Further research
on convective heat transfer on plants is recommended, as well as a spectral reflectivity
measurement of the substrate to improve the accuracy of the model. The next step then will be to
follow what would be a dynamic/transient validation of the model using detailed laboratory data.
Once the model has shown that it can successfully predict the dynamic behavior of green roof
systems, the final step would be to validate it with outdoor data from a green roof.

Once the green roof model is completely validated, the model could be slightly modified
to explore the idea of plant coverage of different parts of the building envelope using green
façades walls systems. This technology is similar to green roofs, with the exception that there is
no substrate covering the rest of the building envelope.

Finally, this research has brought to light the need to treat energy and water as one
interconnected topic in the building design and control systems. It is now evident that water has
an important role on green roof performance, among other building envelope and mechanical
systems, and should be considered when designing building envelope and mechanical system.
Thus, this study hopes to combine what seemed, at the beginning, to be two separate issues.
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Appendix A

Develop of a New Substrate Resistance ($r_{soil}$) Equation for Substrate Evaporation

A new substrate resistance $r_{soil}$ equation for green roof substrate was developed to properly model substrate evaporation based on the experimental data shown in Chapter 6. The decision to develop a new equation for the substrate resistance to evaporation is based on the fact that none of the existing models for soil evaporation achieved good agreement with our experimental data.

All of the soil evaporation models presented in section 2.3.2 and shown in Figure 2-5 were evaluated using bare soil evaporation data from the two experiments without plants in Cold Plate apparatus. Experimental data such as substrate water content and soil evaporation allow for calculation of actual soil resistance when solving for the substrate resistance in Equation (20). In this thesis the procedure to analyze previous soil evaporation models using the experimental data from “Cold Plate” apparatus shown in Chapter 6 was the next:

1. Analyze alpha (Equation (20)), Beta (Equation (20)) and alpha-beta methods (Equation (21)). Following recommendation from a previous study (Mahfouf et al., 1993), these three methods were analyzed in this thesis. Overall the alpha method resulted in a few negative evaporation values when implemented with the “Cold Plate” data. A drawback that has also been reported in the literature (Mahfouf and Noilhan 1991, Ye and Pielke 1993). The Beta method performed better than the alpha-beta method when compared with the measured evaporation rates obtained from the Cold Plate. Thus, the beta method is implemented into the proposed green roof model.
2. Analyze existing models using average volumetric water content in the substrate. Once the beta method was selected, the next step was to compare the seven models shown in Figure 2-5 using same average volumetric water content for all models. None of the models perform appropriately as shown in Figure A-1. This result is not surprising, because most of these models were developed using average volumetric water content for the top 1, 2, or 5 cm layer of the substrate.

![Substrate Resistance Models](image)

**Figure A-1**: Existing soil evaporation models using average volumetric water content in the substrate

3. Develop a new substrate resistance model using half of the experimental data. A new correlation was developed based on six of the twelve days of the experimental data. When compared to the rest of the experimental data, the model performed well except when the substrate is very wet as shown in Figure A-2
4. Analyze models calculating water content profile. This step used measurements from the experiments without plants using Daylight fluorescent lamps. In the 6-day experiment with Daylight fluorescent lamps the substrate volumetric water content was measured at three different substrate depths: (1) bottom, (2) middle, and (3) diagonal or average values. These three measured values were then used to create a non linear volumetric water content profile or also known as “drying front” in the substrate shown in Figure A-3. The non-linear profile is based on field measurements of soil water content profile with similar nonlinear characteristic (Jackson 1973, Hillel 1998).
Once the water content profiles are created, the average volumetric water content as specific layers was calculated using Equation A-1. In Equation A-1, the following substrate depths were used to calculate average volumetric water content: (1) 0-0.5 cm, (2) 0-1 cm, (3) 0-2 cm, (4) 0-5 cm and (5) 0-8 cm. The first four depths were chosen based on the previous depths used by existing soil models (Sun 1982, Camillo and Gurney 1986, Passerat 1986, Kondo et al. 1990, van de Griend and Owe 1994, Olioso et al. 1999). The depth of 0-8 cm was selected to prove the extrapolation and averaging procedure is working properly. Results are shown in Figure A-4. The calculated and measured substrate water contents are very closed.

\[
VWC = \frac{\int_{0.0001}^{Depth} VWC(y) \, dy}{Depth}
\]  

(A-1)
From these profiles calculated in Figure A-4, the average water content for different substrate depths was calculated. Models then were evaluated with the average water content at the depth the model was originally developed for. The new equation for green roof substrate performed better than the rest of the models as shown in Figure A-5. All models performed better than in Figure A-1. Another existing model using 5cm of top substrate water content showed also relatively good agreement (Bussiere 1985). Model 8 is the new equation formulated in this thesis.
Figure A-5: Existing soil evaporation models and new evaporation model using appropriate layers average volumetric water content in the substrate
Appendix B

Selection of Functions to Calculate Stomatal Resistance

Plant transpiration is calculated using Equation (12) and the multiplicative approach proposed by Jarvis (Jarvis 1976) is used in this research to calculate the resistance of the plants to water losses. The equation to calculate the resistance of plants to transpiration is shown in Equation (43) and shown here too.

\[ r_{\text{plants}} = \frac{r_{\text{stomatal min}}}{LAI} \cdot f_{\text{solar}} \cdot f_{\text{VPD}} \cdot f_{\text{vwc}} \cdot f_{\text{Temperature}} \]  \hspace{1cm} (B-1)

Each of the empirical functions “f” in Equation (41) represents a role that each environmental and plant variables, such as solar radiation, VPD and water content, has in transpiration. Different functions were collected from several published SVAT or green roof models (Jarvis 1976, Deordoff 1978, Dickinson 1984, Stahghellini 1987, Stewart 1988, Jacquemin and Noilhan 1990, Avissar and Pielke 1991, Dolman et al. 1991, Oren et al. 1999, Pielke 2002, van de Hurk et al. 2000, Ogle and Reynolds 2002). These functions were developed in different environmental conditions and from different plant types, such as tropical trees or desert shrubs. However, no previous study has evaluated whether these functions are valid in a green roof environment. The functions shown in Figures 2-4 to 2-6 in Chapter 2 were evaluated and compared with experimental data to assess the impact solar radiation, substrate water content, VPD, and temperature have in plant transpiration. Total numbers of functions evaluated are:

5. 9 functions for solar radiation,
6. 8 functions for water content,
7. 6 functions for VPD, and
8. 2 functions for temperature.
Equations (12) and (13) in Chapter 2 were used to calculate plants resistance and to compare stomatal values based on Equation (12) and Equation (13) (Penman-Monteith). In this evaluation, 12 quasi-state steady green roof data sets were used: 6 with low speed and 6 with high speed. The steps followed to calculate each term in Equation (41) are:

1. Minimum stomatal resistance calculation. The value of $r_{\text{plants}}$ for the data set with the highest volumetric water content was used to calculate minimal stomatal resistance, when evapotranspiration was the highest. Equation (12) and Equation (13) were used to calculate the stomatal resistance. Both Equations gave similar results except from a couple of data points. The minimum values in Figure B-1 are 200 and 400 s/m, which using a similar equation to Equation 16 gave 450-1000 s/m, are within the expected range for succulent plants.

Figure B-1: Calculated stomatal resistance from experimental data obtained from “Cold Plate.”

2. Analysis of all functions for stomatal resistance. 19 different combinations of plant stomatal models were tested. Not all possible combinations of functions were analyzed,
because a few functions showed different trends when compared to our experimental data.

Figure B-2: Calculated stomatal resistance from different stomatal models and from experimental data obtained from “Cold Plate.”

3. Selection of the best stomatal model. The models that performed the best are compared in Figure 7-3. The best model incorporates a sub-component for VPD that was empirically developed from desert plants. The model selected is Desert 3 (D-3). There is another stomatal model (r_6) that provided similar performance to Desert 3. However, Desert 3 model was selected because r_6 tend to overestimate minimum stomatal resistances. Overall, the model performed well, but tends to overestimate stomatal resistance when the substrate has high volumetric water content.
Figure B-3: Sub-components with closer agreement to calculated stomatal resistance from experiments.

The functions selected to calculate stomatal resistance are:

\[
f_{\text{solar}} = 1 + e^{-0.034(R_s-3.5)}
\]  

(44)

\[
f_{\text{VWC}} = \begin{cases} 
1 & \text{VWC} > 0.7VWC_{fc} \\
VWC_{fc} - VWC_{wp} & \text{VWC}_{wp} < \text{VWC} < 0.7VWC_{fc} \\
\frac{VWC - VWC_{wp}}{1000} & \text{VWC}_{wp} > \text{VWC}
\end{cases}
\]  

(45)

\[
f_{\text{VPD}} = \frac{1}{1 - 0.411\ln\left(e_{s,\text{plants}} - e_a\right)}
\]  

(46)

\[
f_{\text{temp}} = \frac{1}{1 - 0.0016\left(30 - (T_{\text{plants}} - 273.15)\right)}
\]
Appendix C

Plant Surface Temperature

As explained in section 5.1 and section 6.2.3, plant temperature was measured by 4 thermistors attached to leaves. Unfortunately, this technique might not measure plant temperature very accurately; despite the thermistors’ accuracy of ±0.2°C. This is because only half the area of the sensor is in contact with the leaf and the other half is exposed to air temperature and incoming radiation. Incoming radiation was minimized by coating the thermistors with aluminum foil. However, to address this weakness in the temperature measurement, an infrared (IR) camera was used during the last day of some experiments to take infrared pictures of the green roof samples. Thus, analysis of the infrared pictures can confirm the surface temperature values from the thermistors.

Figures C-1 (a) and (b) show pictures of green roof samples with all sensors in place. The red circles show the approximate locations of the thermistors measuring plant surface in (a) Baseline experiment and (b) Baseline II experiment. Figures C-2 (a) and (b) show the pictures taken from the IR camera for (a) Baseline experiment and (b) Baseline II experiment. Digital processing of the IR pictures as well as their statistical analysis was performed in ThermaCAM Researcher Pro 2.8. This software is developed by the same company that manufacturers the IR camera. The comparison between thermistors’ point measurements and IR temperature area-average surrounding the point showed that readings from the IR camera were consistently higher by 1-2°C. However, this difference is within the uncertainty of the IR camera of ± 2°C. Moreover the standard deviation from each temperature area-average around the point measured was 0.8-1°C.
Likewise, the average plant temperature from all thermistors installed on the leaves was consistently lower than the area-average plant temperature obtained by the IR camera by 0.5-2 °C. Standard deviation from the entire green roof sample increases to about 1.5-2°C. Figure C-3 shows the histogram for the surface temperature for the Baseline II experiment. Temperature distribution looks normal and about 68% of the data is located at -1 and 1 standard deviation (1.4 °C.) from the mean (37.2°C).
Figure C-3: Plant surface histogram for the green roof sample during Baseline II experiment. Horizontal axis represents surface temperature divided in 10 bins. Vertical axis represents percentage of data points.

Figure C-4 (a-e) shows the surface temperature histogram for each area circle shown in Figure C-2(b). All figures are graphed with the same horizontal axis scale (32.1-43.7°C). Most of the figures are centered on the total area average (37.2°C), although slightly skewed and/or shifted from the mean. The highest temperature difference between all area points is around 3°C or about two standard deviations. The highest temperature difference is located between the upper right circle (circle 2 in Figure C-2b) and lower left circle (circle 4 in Figure C-2b).
Figure C-4: Plant surface histograms for areas (a) 1, (b) 2, (b), 3, (d) 4 and (e) 5 shown in Figure C-2(b). Values come from the green roof sample during Baseline II experiment. Horizontal axis represents surface temperature divided in 10 bins. Vertical axis represents percentage of data points.
Appendix D

Statistical Analysis of Model Performance

Verification

Figure D-1: (a) Normal probability plot and (b) histogram of model convection normalized bias.

Figure D-2: (a) Normal probability plot and (b) histogram of model evapotranspiration normalized bias.
Validation

Figure D-3: (a) Normal probability plot and (b) histogram of model conduction normalized bias.

Figure D-4: (a) Normal probability plot and (b) histogram of model convection normalized bias.

Figure D-5: (a) Normal probability plot and (b) histogram of model evapotranspiration normalized bias.
Figure D-6: (a) Normal probability plot and (b) histogram of model conduction normalized bias.

Figure D-7: (a) Normal probability plot and (b) histogram of model substrate temperature normalized bias.

Figure D-8: (a) Normal probability plot and (b) histogram of model plant temperature normalized bias.
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