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An investigation of sensible heat fluxes at a green roof in a laboratory setup

Tahir Ayata [a,b,*], Paulo Cesar Tabares-Velasco [a], Jelena Srebric [a]

[a] Department of Architectural Engineering, Pennsylvania State University, University Park, PA 16802, USA
[b] Kayseri Vocational College, Erciyes University, 38039, Turkey

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ABSTRACT

During the last few years, several models have been proposed for the calculation of green roof thermal behavior, but the validation studies of such models are lacking a comprehensive set of highly accurate data. In this study, an experimental laboratory setup was used to create different environmental conditions and to measure sensible heat fluxes to/from a vegetated roof assembly. This experimental setup has been successfully used for different wind velocities (0–3 m/s) to create free and forced convection conditions around green roof tested samples. Furthermore, our study proposed a “basic model” for calculations of the convective heat transfer at green roof assemblies, which is a modified version of the Newton’s cooling law, calibrated and then validated with different sets of data. For forced convection flow regimes, the proposed “basic model” resulted in RMSE (Root Mean Square Error) of 11 W/m^2 and R^2 value of 0.81. Similarly, the model provided RMSE of 6.6 W/m^2 and R^2 of 0.90 for sensible heat fluxes with free convection conditions. In the future, this model will be used in on-site experimental studies to understand its performance under wind conditions that exhibit a much wider range than the studied velocity range near the leaf canopy.

1. Introduction

Vegetation has been used on building roofs and walls since ancient times, with the most famous example of the Babylonian gardens in Mesopotamia. A widespread use of roof vegetation has significantly increased in recent years. Fig. 1 shows an example of contemporary use of vegetation for a traditionally-designed house in Norway. Some European countries have explored opportunities for use of extensive green roofs since the 1970s [1]. The specific purposes of green roof installations vary, but generally hinge upon stormwater reduction or improved building energy efficiency and often both. As stormwater concerns in urban settings have become ubiquitous, green roofs have been introduced as a viable and effective method for reducing urban stormwater runoff from roof surfaces [2].

The types of growing media and roof assemblies vary, but most green roofs consist of a drainage layer, a root barrier, and a waterproof membrane as shown in Fig. 2. A green roof growing media depth is typically between 0.05 and 0.3 m [3], while the vegetation layer can incorporate different plants depending on the local climate [4]. A green roof has numerous benefits that include improved air quality, reduction of the “heat-island effect,” sound attenuation, building envelope protection, esthetic value, and stormwater detention, in addition to the reduction of energy absorbed by the roof assembly [2,5–7]. One of the ecological functions a green roof provides is its stormwater management capacity. Nevertheless, to take full advantage of green roofs, building designers need quantitative assessments of green roof benefits.

Horizontal building surfaces, such as roofs, experience high thermal loads during summer conditions in climates such as the Mediterranean or some U.S. climate regions. Green roofs may offer an adequate solution to this problem [8]. Theoretical and experimental analyses of different roof assemblies to promote cooling mostly focuses on evaporative and radiative heat transfer mechanisms. The green roof vegetation shades this type of roof assemblies from direct solar radiation, and it also cools the roof by means of evapotranspiration from the vegetation layer [9]. The vegetation layer also absorbs large quantities of solar energy during the diurnal biological functions. An incoming amount of solar radiation can affect the internal temperature of a building. Out of the total incoming solar radiation, approximately 27% is reflected, 60% is absorbed by the plants and the soil through evaporation, and 13% is transmitted into the soil [10,11]. As a result, green roofs can control the temperature of the roof assembly and protect the roof membrane from temperature extremes. During summer weather

* Corresponding author. Department of Architectural Engineering, Pennsylvania State University, University Park, PA 16802, USA.
E-mail address: tahirayata@yahoo.com (T. Ayata).

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Fig. 1. Traditional green roof with native vegetation in Norway [1].

conditions, the vegetation and soil layers can reduce the cooling energy costs for buildings, such as warehouses, which have a relatively large roof area when compared to the vertical wall area of such buildings [12].

Greenroofing in the world is a burgeoning industry. With the spread of greenroofing comes the need to understand and predict the thermal effects associated with adding a soil and vegetation layer to a building envelope. Several previous studies have evaluated the thermal properties of green roofs. It is well known that vegetated roof coverings, or green roofs, can lower rooftop surface temperatures in warm climates [7,9,13]. The magnitude of temperature reduction and resulting reduction of heat flow into structures is dependent upon many factors associated with a green roof's construction and with the climate of the area. Cooler surface temperatures translate into decreased heat transfer through roofs into the occupied space thereby reducing cooling loads in warm months.

In both cool and humid climates, evaporative potential limits the cooling effects transpiration and evaporation provide. However, in a study conducted in Singapore (wet and tropical conditions), it has been observed that vegetation can consume solar heat gain through evapotranspiration and photosynthesis [14]. This consumption of solar heat implies that passive cooling is occurring. In cooler areas, other parameters including thermal mass may become significant factors in determining green roof thermal performance, where performance in this case is equated with heating load reduction. This study reveals that, rooftop vegetation caused a negative heat flux during most of the day compared to a positive, downward heat flux for an adjacent bare roof, in a tropical environmental [14].

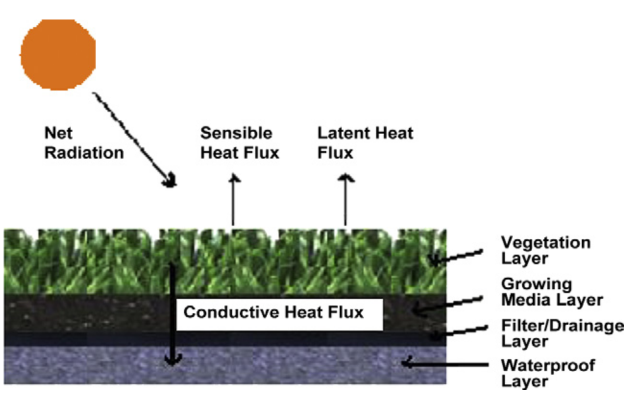


Fig. 2. A schematic of a typical green roof layers, and energy balance at the vegetation layer.

Other studies have revealed similar passive cooling capabilities. They describe green roof effects in Mediterranean climates where wet winters and dry summer conditions dominate. In addition, planted roofs not only insulate, but also can provide passive cooling for building interiors via evaporative cooling [7,9,15]. A limited number of studies have observed green roof effects in winter. In one such study it is predicted that soil moisture, a thermal mass contributor, may be the essential factor in the insulating capacity of green roof systems in winter [9].

An experimental study measured and also calculated sensible heat fluxes to/from a green roof sample using a formulation suggested by Wang [16] in a laboratory environment [11,17]. However, in these studies, sensible heat fluxes were obtained indirectly from an energy balance, and the suggested equations for sensible heat flux calculations are only strictly valid for free convection conditions. Thus, the main purpose of the present paper is to develop a model for sensible heat flux calculations at a green roof with different convection conditions. In addition, different theoretical and semi-empirical methods are compared with experimental sensible heat flux data obtained from a new experimental apparatus, cold plate, under controlled laboratory conditions. In this study, three different types of convective heat transfer models are compared, and effects of the green roof with different airflow velocities are considered for free and forced convection regimes.

2. Methodology and theory

Understanding sensible heat fluxes at surfaces covered with a plant material is challenging because the surface is rough and porous. Moreover, surface temperature distribution is not homogeneous because the leaf temperature depends on many factors such as sensible and latent heat transfer, which change depending on several environmental parameters. The vegetation layer behaves as an attenuator of heat fluxes in a green roof. This effect must be taken into account for calculations of sensible and latent heat fluxes. Previous studies have followed experimental and theoretical methodologies to understand the thermal behavior of vegetated roofs. In a majority of these experimental studies, the thermal behavior of vegetated roof assemblies was investigated using the environmental weather conditions [18]. A few laboratory studies also attempted to understand the thermal behavior of plant materials [19]. All of the existing studies looked at the thermal behavior based on the overall energy balance for the roof assembly with the exception of one laboratory study with a cold plate apparatus, which provided detailed data on all important heat transfer mechanisms individually [11,17,20]. In this study, additional experimental data were collected in the cold plate apparatus to include different airflow regimes. Furthermore, convective heat transfer at a green roof was examined with different theoretical models and the model predictions were compared to measured data.

2.1. Energy balance

Several authors suggested time dependent energy balance approach for modeling green roof heat fluxes as shown in Fig. 2 [11,15,21–23]. All relevant energy fluxes should be considered when calculating an energy balance as following:

$$R_n - G - L - H = 0 \quad (1)$$

where R_n is the net radiation [W/m^2], H is the sensible heat flux [W/m^2], G is the soil heat flux [W/m^2], and L is the latent heat flux

[W/m^2]. All terms in Equation (1) can be either positive or negative. For example, negative sensible heat fluxes deliver energy to the roof surface and positive H removes energy from the roof assembly as shown in Fig. 2. Other energy terms, such as the heat stored or released by the plant material, or the energy used in metabolic activities, are not considered because they are negligible [24].

The latent heat flux represents the evapotranspiration rate of vegetation layer and growing media underneath the plants. Evapotranspiration rate can be directly measured by measuring the rate of water losses from a roof assembly. Net radiation R_n and soil heat fluxes G can also be measured from experimental setup or calculated using related equations once the surface temperature of the plants and growing media are known. However, measurements of the sensible heat flux are complex and cannot be easily obtained. H requires accurate measurement of temperature gradients above the surface and all layers of experimental setup. Nevertheless, H can be calculated from the energy balance equation, if all other equation terms are known.

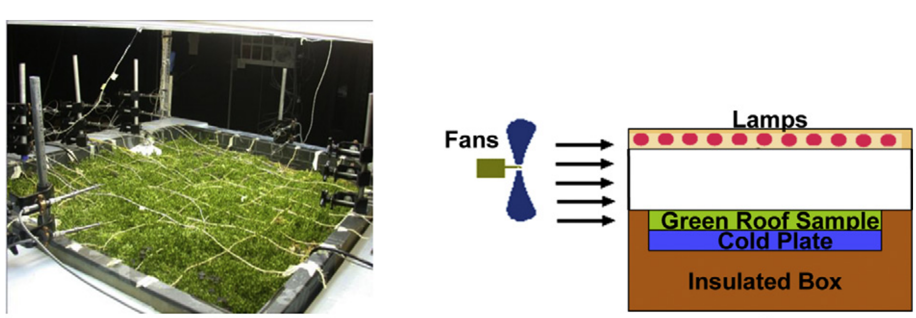
In energy balance calculations, vegetation density can be accounted for by the leaf area index (*LAI*). *LAI* is defined as the single-side leaf area per unit ground area. *LAI* is a dimensionless number that was calculated for the green roof sample in this study. *LAI* was defined as $LAI = S/2G$, where S is the functional (green) leaf area of the canopy standing on the ground area G. Since both of terms, S and G, are measured as areas (m^2), *LAI* is dimensionless. Most commonly, S is measured as the projected area after placing a sample leaf on a horizontal surface. Another way of measuring *LAI* is by measuring the total surface area of leaves in a canopy. This area is equal to 2S for flat leaves and greater than 2S for needle-shaped, succulent leaves, and photosynthetic stems [25,26]. In our study, we used the second method to measure *LAI* that resulted in an *LAI* range from 2.3 to 2.7 for the tested samples.

2.2. Experimental setup and green roof sample description

The experimental data used were obtained from several experiments inside an environmental chamber. An apparatus was designed and built to measure important heat and mass transfer processes in green roof assemblies [11,20]. The apparatus is called, “Cold Plate,” and is located inside a real-scale environmental chamber that controls environmental parameters such as air temperature and humidity. The cold plate 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 for use of laboratory-rated acquisition equipment. The cold plate apparatus is instrumented with different data acquisition sensors (Water Reflectometer, Thermistors, Heat Flux Meters, Anemometer and Pyranometer). Fig. 3(a) and (b) shows a photo of the cold plate experimental setup and its schematic representation, respectively. A more detailed description of the cold plate apparatus is found in the literature [17]. The cold plate apparatus consists of a strongly insulated box ($R \approx 10.6$ m^2 K/W = 60 ft^2 h °F/Btu) that holds a green roof sample. A hydronic system keeps the lower part of the green roof sample at a lower temperature than the temperature of its surrounding air.

This arrangement is simulating cooler indoor conditions for buildings in summer. Furthermore, artificial lighting was provided by either UVA/visible lamps with an irradiance of about 160 W/m^2 or by daylight fluorescent lamps with an irradiance of 110 W/m^2. Irradiance was measured by a secondary class standard pyranometer in the spectral range of 305–2800 nm (see Fig. 3(a)). The net radiation (R_n) was calculated by measuring the incident solar radiation intensity simultaneously with pyranometer. Evapotranspiration in this study was measured using both the lysimeter and water balance methods. The lysimeter method is considered a direct method to measure evapotranspiration as it records weight changes due to water losses from evapotranspiration [27]. The lysimeter in this study used a scale, robust enough to hold a weight of 300 kg and sensitive enough to detect up to a 0.002 kg change in weight. The soil water balance approach is an indirect method to estimate evapotranspiration, as evapotranspiration is calculated from the residual term after applying a water balance equation [27]. The soil water balance approach was based on the substrate water content measurements. The lysimeter and water balance methods have been previously used in other green roof studies [28–30].

The list and description of each sensor and variable measured are extensive and located in the literature [17,20]. Heat fluxes measured during experiments include: (1) incoming short and long wave radiation, (2) latent heat flux, and (3) heat flux through the green roof sample. The convective heat flux was calculated from Equation (1) once all of the other fluxes were independently measured. Thus, the accuracy of the calculated convective heat transfer depends on the accuracy of each heat transfer measurement. Overall, in our experiments, the compounded accuracy for convective heat transfer is ± 11 W/m^2, which was estimated for the collected experimental data with the Root Mean Square Error calculation method. Additionally, the temperature of the substrate was measured with 5 waterproof thermistors slightly covered by the substrate. In contrast, the plant temperature is more challenging to measure, as the leaf temperature varies depending on different factors such shading from other leaves. The leaf temperature can also change from the top part of the leaf that is being directly heated by radiation to the bottom part that is protected by the top part. Thus, the leaf temperature was measured using 5 thermistors attached to the leaves and coated with aluminum foil to minimize radiative noise. The leaf temperature was also measured by an infrared camera at the end of each experiment to corroborate the results.



a b

Fig. 3. (a) A photo of the green roof experimental setup inside the environmental chamber, and (b) A schematic representation of the experimental setup.

The tendency for increased variety and diversity at community junctions is known as the edge effect. In the case of a forest, where the adjacent land is typically cut, creating an open/forest boundary, sunlight and wind penetrate to a much greater extent, drying out the interior of the forest close to the edge and encouraging growth of opportunistic species at the edge. The air temperatures and soil moisture content change at edges. The airflow near a building wall edge is also more complex than that of the inner part of those walls because of the separation vortex at a critical wind velocity. The convective heat transfer coefficient for a building edge wall is much higher than that near the wall center. The effect of edge in building walls could be seen in a study conducted by Hagisima et al. for different wind velocity values (0–3 m/s) [31,32]. Fig. 3(b) shows a schematic representation of the experimental setup and the green roof sample insulated at the bottom and all four sides of the sample. Therefore, thermal symmetry for the heat transfer modeling is applicable as well as the assumption of homogeneously covered vegetation areas. The edge effect is assumed to be negligible in this experimental model due to a high level of insulation for the sample box.

By using the cold plate inside the environmental chamber, the authors were able to test the sample under different environmental conditions. Each experiment consisted of 14 h with constant artificial lighting and 10 h of darkness. The long "daylight" period was selected to resemble summer conditions and to obtain quasi-steady-state conditions by setting the air temperature to be 28 °C in the return air duct of the environmental chamber. The actual air temperature, just above the plants, was measured by a set of hot-sphere anemometers. The air temperatures in locations near the plants were slightly higher than the exhaust temperature. All values (temperature, velocity and humidity term) have been measured at different positions and levels (soil, vegetation and air) as shown in Fig. 3(a). Green roof samples were watered 48 and 24 h before commencement of the experiments. Once all sensors were installed, the chamber was closed to minimize any interaction with the outdoor environment. Table 1 presents the number of days for each experiment defined as a case, as well as mean airflow velocities U [m/s], vegetation coverage ratios σ, and leaf area indices LAI for different cases.

The tested sample contained *Delosperma nubigenum* plants, which are sedum plants typically used in green roof systems. The plant samples were contained in boxes of outer dimensions of 1.30 m by 1.1 m to fit the cold plate apparatus. The vegetation layer was in a fully-grown condition at the time when the experiments were conducted. Thus, as shown in Table 1, plants provided 90–100% surface area coverage depending on the specific sections of the roof sample. Furthermore, the thickness of the soil layer is usually determined by the size and type of the selected vegetation. It can vary from 0.05 m to even more than 1.0 m in different roof assemblies [3]. In this study, the soil depth was 0.09 m, which is considered to be sufficient for the experimental green roof assembly with sedum plants.

Table 1
Number of Days, Mean velocities, Coverage ratio and Leaf Area Index for different experimental cases.

Case	No. Days	U (m/s)	σ	LAI
1	4	0.11	0.9	2.3
2	6	0.13	1.0	2.3
3	3	0.5	1.0	2.7
4	6	1.1	0.95	2.3
5	2	2.0	1.0	2.7
6	5	3.0	1.0	2.7

3. Sensible heat flux calculations

Accurate calculations of sensible heat fluxes are important because the energy balance equation cannot be effectively used without this term. Therefore, the main purpose of this study was to describe methods for calculating sensible heat flux from/to the vegetation layer. Previous experimental studies have used equations for convection to/from rectangular flat plates and other geometrically simple objects under various conditions. However, these idealized conditions are not directly applicable to green roofs because the recommended calculation methods assume geometrical similarity. Thus, our study investigated whether the available equations for calculations of sensible heat fluxes can be modified and used for the vegetation layer.

The fundamentals of sensible heat flux calculations can be found in the literature as Newton's law of cooling [33,34]. This fundamental method needs modification for calculations of sensible heat fluxes at the vegetation layer, which will be explained in more details. Under given conditions, such as airflow speed, air pressure, and temperature, the convective heat transfer rate is calculated between the leaf and the air using the leaf area and temperature difference between the air and leaf surface. If the convection coefficient h [W/m^2 K] is known for a given surface, such as vegetated roofs, then the sensible heat flux to/from the surface, H, is given by:

$$H = h(T_l - T_a), \tag{2}$$

where T_l is the mean leaf temperature [K], T_a is the air temperature [K], and H is the sensible heat flux [W/m^2].

Forced and free convection of heat are usually taken into account in the dimensionless form of Nusselt (Nu) number, which is a function of Reynolds (Re) and Prandtl (Pr) numbers. In free convection, the Grashof number (Gr) is also used for different dimensionless correlations. The most relevant free, mixed, and forced convection correlations are reviewed.

3.1. Non-dimensional correlations for heat fluxes in free, mixed, and forced convection

The calculation of the Nu number for the convective heat flux over a rectangular plate at uniform temperatures in a steady-state with laminar airflow is given as the following:

$$\mathrm{Nu} = hL/k = 0.664\mathrm{Pr}^{0.33}\mathrm{Re}^{0.5}, \tag{3}$$

where L is the characteristic length. The characteristic length for Re is $L = 4A/C$, where A is the plate area and C is its circumference. For a rectangular plate, with sides L_1 and L_2, the characteristic length becomes:

$$L = \frac{2L_1L_2}{L_1 + L_2}. \tag{4}$$

The general equation for forced convection has been represented non-dimensionally as the following:

$$\mathrm{Nu} = C\cdot\mathrm{Pr}^{0.33}\mathrm{Re}^{n}, \tag{5}$$

where C is a constant and n is an exponent dependent on the fluid flow regime. In the case of transition from laminar to turbulent boundary layer flow, the exponent n takes a value of 0.8 [35,36]. The following equation is recommended for local and average dimensionless heat flux for horizontal flat plates with a uniform surface temperature [37]:

$$\mathrm{Nu} = 0.037\cdot\mathrm{Pr}^{0.33}\mathrm{Re}^{0.8}. \tag{6}$$

The critical Reynolds value Re_{cr} for transition to turbulence in the boundary layer depends on the surface geometry, surface roughness, free-stream velocity, surface temperature, type of fluid, and a number of factors that cannot be easily defined. For flow over a flat plate, the generally accepted value of the critical Reynolds number is $Re_{cr} = 5 \times 10^5$ [34]. A more realistic value of Re_{cr} is 2×10^4 for vegetation based on flat, rectangular leaf models [38,39]. Semi-empirical dimensionless expressions have been derived for leaf fluxes in free convection using the Grashof number. Heat and mass fluxes are represented in dimensionless relationships as following:

$$\mathrm{Nu} = k \cdot \mathrm{Pr}^m Gr^n. \tag{7}$$

Classical heat flux analyses for free convection of the upper surface of horizontal, cooled plates typically use the following expressions [33]:

$$\mathrm{Nu} = 0.54 \cdot \mathrm{Pr}^{0.25} \mathrm{Gr}^{0.25} \tag{8.a}$$

for $10^4 < \mathrm{Gr} < 10^7$.

$$\mathrm{Nu} = 0.15 \cdot \mathrm{Pr}^{0.33} \mathrm{Gr}^{0.33} \tag{8.b}$$

for $10^7 < \mathrm{Gr} < 10^{11}$.

Usually, a long flat plate is sufficient for the flow to become turbulent, but not long enough to neglect the laminar flow region. In such conditions, the Nusselt number over the plate is determined by taking into account the critical Reynolds number to be $Re_{cr} = 5 \times 10^5$:

$$\mathrm{Nu} = \left(0.037 \cdot \mathrm{Re}_L^{0.8} - 871\right) \mathrm{Pr}^{0.33} \tag{9}$$

for $5 \times 10^5 < \mathrm{Re}_L < 10^7$.

The constants in these equations will be different for different critical Reynolds numbers. If this equation is reformulated for $Re_{cr} = 2 \times 10^4$, a new equation emerges for rectangular leaf models [40], and an average Nusselt number over the entire vegetation area is found to be:

$$\mathrm{Nu} = \left(0.037 \cdot \mathrm{Re}_L^{0.8} - 8.2\right) \mathrm{Pr}^{0.33} \tag{10}$$

for $2 \times 10^4 < \mathrm{Re_L}$.

For low airflow velocity values, the transitional flow regime conditions have been less extensively studied than for free or forced convection. A criterion was developed to define the transition between free and forced convection on the basis of the $\mathrm{Gr}/\mathrm{Re}^2$ ratio. However, the transition region called mixed convection, is not sharply defined; semi-empirical criteria set the limits for 5% departure from the pure free or forced convection at $0.1 < \mathrm{Gr}/\mathrm{Re}^2 < 16$ [40]. Typically, the heat transfer for the mixed convection regime was determined by calculating Nu number for both forced and free convection using Equations (9) and (10). The calculated Nu numbers were evaluated, and the greater of the two Nusselt numbers would be chosen to represent the mixed convection regime. Alternatively, it is possible to treat resistances due to two convection regimes in parallel, and the Nusselt number could be a sum of the calculation for free and forced convection Nusselt numbers [41]. Detailed analysis of data for flat, horizontal plates from a variety of sources suggests the following equations for Nu number for the mixed convection regime [42]:

$$\mathrm{Nu}_{\mathrm{forced}}^2 = \mathrm{Nu}_{\mathrm{laminar}}^2 + \mathrm{Nu}_{\mathrm{turbulent}}^2 \tag{11.a}$$

$$\mathrm{Nu}_{\mathrm{total}}^{3.5} = \mathrm{Nu}_{\mathrm{free}}^{3.5} + \mathrm{Nu}_{\mathrm{forced}}^2 \tag{11.b}$$

Overall, the reviewed equations provide non-dimensional models for free, mixed, and forced convection that were adopted from the experiments with flat plates, and minor modifications for vegetated surfaces such as Equation (10). Nevertheless, there are several models specifically developed for surfaces covered with vegetation.

3.2. Calculation methods for surfaces covered with vegetation

In addition to the reviewed non-dimensional correlations, surfaces with vegetation have additional experimental correlations for calculations of sensible heat fluxes. Semi-empirical and empirical approaches were used to develop these correlations for vegetated surfaces. For the semi-empirical approaches using the logarithmic wind profile, the fundamental Newton's law was modified to include parameters that specify plant material characteristics important for convective heat transfer [48]. The empirical approaches, such as McAdams' Method, define correlations or the convective heat transfer coefficients based on experimental measurements [49].

3.2.1. Logarithmic wind profile method

If temperature and wind speed observations at different elevations above a surface are available, then the following equation is used in the Penman–Monteith model to calculate the aerodynamic resistance to sensible heat transfer [50]:

$$H = \frac{\rho \cdot C_p (T_s - T_a)}{r_a} \tag{12}$$

where T_s is the surface temperature [K], T_a is the air temperature above the surface [K], $\rho \cdot C_p$ is the volumetric heat capacity [J m^{-3} K^{-1}], and r_a is the air resistance to heat flux [s m^{-1}]. The air resistance term can be calculated as following [53]:

$$r_a = \frac{\left[\dfrac{\ln(z-d)}{z_m} + \psi_m\right]\left[\dfrac{\ln(z-d)}{z_h} + \psi_h\right]}{k^2 u} \tag{13}$$

where d, z_m and z_h are displacement height, roughness length for momentum, and scalar roughness for heat, respectively [m]. $k = 0.4$ is von Karman's constant, u is the wind speed [m s^{-1}] at height z, and ψ_s and ψ_m are stability corrections for heat and momentum.

The wind speed is lowest at the surface and increases with height due to no-slip boundary conditions at the surface. A logarithmic wind speed profile may be used for measurements above a short grassed surface [48]:

$$u = \frac{u^*}{k}\left[\frac{\ln(z-d)}{z_m} + \psi_m\right] \tag{14}$$

and

$$u^* = \left(\frac{\tau}{\rho}\right)^{\frac{1}{2}} \tag{14.a}$$

where u^* is the friction velocity [m/s], τ_0 is the surface shear stress [N/m^2] and ρ is the air density [kg/m^3] [52]. Equation (14) converts meteorological wind data to the local wind velocities for sensible heat flux calculations at the vegetation level. Wind velocity has been measured at different elevations above the green roof sample as shown in Fig. 4(a). A sample of mean velocity data for forced convection is given in Fig. 4(b). Because the measured wind velocities were available at the roof sample elevation, Equation (14) was not used for a calculation of the air resistances.

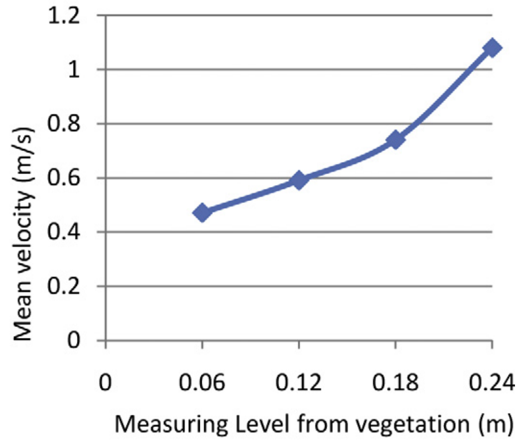


Fig. 4. (a) Anemometers measuring air velocities at three different elevations near the green rood sample surface, and (b) measured sample mean velocities above the green roof sample for forced convection.

For a wide range of crops, the zero plane displacement height, d [m], and the roughness length governing momentum flux, z_m [m], can be estimated from the crop height h by the following equations:

$$d = \frac{2}{3}h \tag{14.b}$$

$$Z_m = 0.123h \tag{14.c}$$

The roughness length governing flux of heat and vapor, z_h [m], can be approximated by [26]:

$$z_h = 0.1z_m \tag{14.d}$$

The temperature difference between the air and vegetation near the ground surface causes overturning of the air layers, and results in increased turbulence and mixing. This turbulence is related to sensible heat flux (H) at the vegetation surface. If the vegetation surface is hotter than the air, and also sensible heat flux is positive, the surrounding atmosphere of vegetation is unstable, and mixing is increased. Meanwhile, if sensible heat flux is negative, the atmosphere is stable, and mixing is minimal. If local heating or cooling at the vegetated surface is present, corrections in Equation (14) is made and referred to as adiabatic corrections. The profiles of adiabatic correction factors are given as the following: For unstable flow

$$\psi_h = -2\ln\left[\frac{1+(1-16\xi)^{\frac{1}{2}}}{2}\right] \tag{15.a}$$

$$\psi_m = 0.6\psi_h \tag{15.b}$$

For stable flow

$$\psi_m = \psi_h = 6\ln(1+\xi) \tag{16}$$

where ξ is the ratio of convective to mechanical production of turbulence, and it can be used as a measure of atmospheric stability [51]:

$$\zeta = -\frac{k \cdot g \cdot z \cdot H}{\rho \cdot C_p \cdot T \cdot u^{*2}} \tag{17}$$

3.2.2. McAdams' Method

When forced convection dominates over free convection and if leaf area sizes are relatively small, the empirical relationship formalized by McAdams should be used [51]. This equation can be used for flat surfaces larger than the leaf size and $u < 5$ m/s as the following:

$$h = 5.9 + 4.1u\frac{511+294}{511+T_a} \tag{18}$$

where u is wind speed [m/s] adjusted for T_a [K]. It is assumed that conditions on each side of a thin leaf are similar, and, therefore, temperatures and convective heat transfer coefficients are assumed to be the same at the bottom and top sides of each leaf. In general, due to the gravity forcer, a heat flow upwards from a horizontal surface will be greater than a heat flow downwards, especially for the free convection. The tested sample contained *D. nubigenum* plants, which are sedum plants typically used in extensive green roof systems. Fig. 5 shows plants that have a symmetric leaf structure, which can be assumed to have equal two-sided heat transfer rates for both forced and free convection conditions. Therefore, h values can be doubled for a two-sided leaf:

$$H = 2h(T_l - T_a) \tag{19}$$

Fig. 5. *Delosperma nubigenum* plants with a leaf structure available for heat transfer at both upper and lower leaf sides.

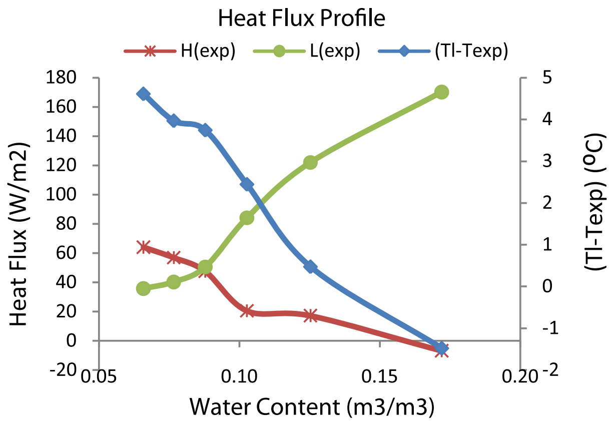


Fig. 6. Sensible and latent heat fluxes and temperature difference variations with volumetric water content.

where T_a is the air temperature at standard height above the ground surface [K], and T_l is the leaf temperature [K]. This model was used for a leaf wetness model to estimate dewfall amount on a roof assembly top surface [56].

4. Results and pre-discussion

For energy balance calculations at a green roof assembly, net radiation to the vegetation from sky and sun, latent and sensible heat flux to/from the vegetation layer, and heat conduction at the soil layer must be known. Net radiation and heat conduction to the soil layer can be calculated easily with the existing models [11]. However, calculation of latent heat flux from the vegetation layer is not trivial [11]. There are several methods for latent heat flux calculations from a vegetation layer. One of these methods is the Penman–Monteith Method for estimation of latent heat fluxes at the vegetation layer [48].

Our previous studies measured and also calculated the sensible heat flux to/from vegetation layer using this method for green roof samples in a laboratory environment [11,20]. This study calculated sensible heat fluxes by using the energy balance of a green roof as well as using the model developed by Wang [18]. However, these calculations produced sensible heat fluxes from the energy balance in mostly free convection conditions. Therefore, the present study calculates the sensible heat fluxes based on the overall energy balance at the green roof sample for both forced and free convection regimes. The present study uses Newton's law, the Logarithmic Wind Profile method and, McAdams' method for the assessment of sensible heat fluxes in free and forced convection regimes. As shown in Fig. 6, the temperature difference between the vegetation layer and surrounding air decreases with the increase in the soil water content. Thus, the sensible heat flux decreases and latent heat flux increases with the increase in the soil water content.

A previous study investigated heat fluxes from a green roof for two types of soil (light soil 1100 kg/m^3 or heavy soil 1500 kg/m^3) as well as the effect of soil moisture content on the thermal conductivity of soil [9]. When the density of soil decreases, the thermal conductivity is decreased and the heat flux through the roof is also reduced. The soil moisture content determines the soil thermal diffusivity as well. The soil thermal diffusivity increases with the apparent density, and decreases with the soil moisture content. This present study used light-weight soils (640 kg/m^3) with different soil water contents for calculation of heat fluxes from the green roof. Fig. 6 demonstrates the effect of the soil water content on the heat fluxes from the green roof.

The main parameters for accurate calculations of sensible heat fluxes are the convective heat transfer coefficient and the temperature difference between the surface (vegetation) and fluid (air). The convective heat transfer is related to the Reynolds number and also is related to the local air velocities and temperature difference. When dealing with vegetated roofs, this calculation needs new parameters because of increased surface area and roughness due to the vegetation layer. The effects of increased surface roughness are accounted for by the vegetation coverage ratio (σ) and the increased area is accounted for by the leaf area index (*LAI*). For calculations of the convective heat transfer coefficient, a few authors adopted a surface roughness of vegetation layer or they defined a new characteristic length for the vegetation layer. A choice of adopting the surface roughness or defining a new characteristic length is related to the difference between the real surface area available for heat convection and the surface area covered with vegetation. Therefore, a modified version of Newton's law can be used for calculation of sensible heat fluxes to introduce vegetation parameters such as σ and *LAI*. The modified form of Newton's law, Equation (2), for the sensible heat flux equation can be postulated in the following form:

$$H = LAI \cdot h(T_l - T_a) \tag{20}$$

This modified form of Newton's cooling law has been used by two earlier studies [7,11]. This calculation for the sensible heat flux calculations is similar to the Deardorff's equation, which was used for calculations of sensible heat fluxes in a previous study [54]. The

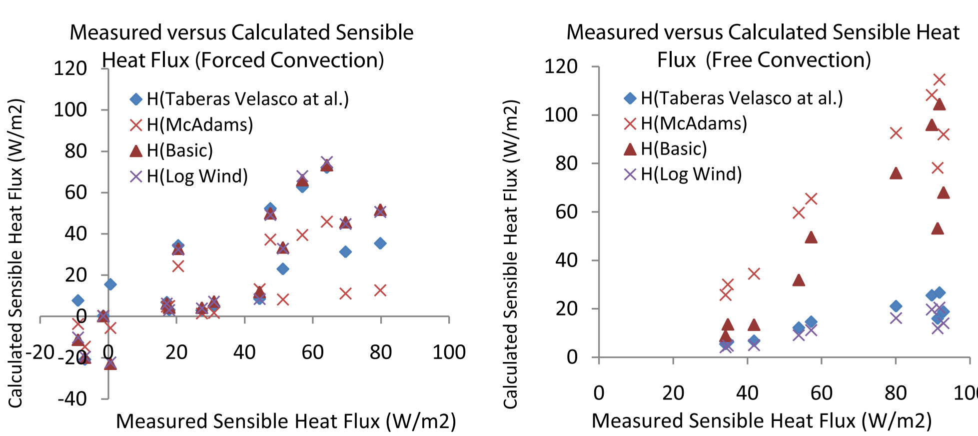


Fig. 7. Measured versus calculated sensible heat fluxes for forced and free convection flow regimes.

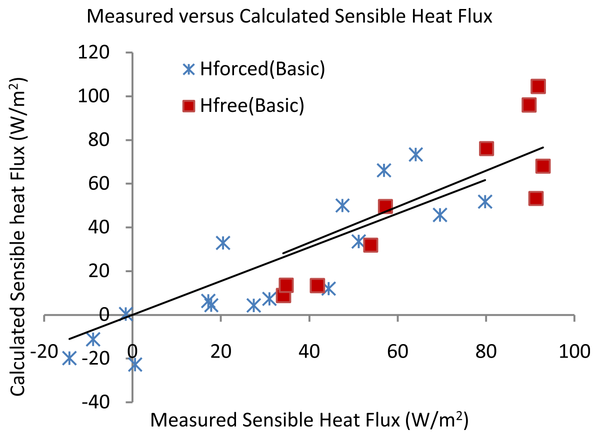


Fig. 8. Comparison between measured and calculated sensible heat fluxes for forced and free convection flow regimes.

sensible heat flux for a unit area of the horizontal vegetated ground surface is given by the following Deardorff's equation:

$$H = 1.1 LAI \cdot \rho_{af} C_p C_f U_{af} \cdot \left(T_l - T_{af}\right) \quad (21)$$

where ρ_{af} is the air density in the close proximity to the foliage [kg/m^3], C_p is the specific heat of air at constant pressure [J/(kg K)], C_f is a dimensionless heat transfer coefficient that takes into account both sides of a leaf [−], U_{af} is a mean wind velocity that both ventilates the foliage and promotes a weak heat and moisture fluxes [m/s], T_l is a representative leaf temperature [K], and T_{af} is a mean air temperature within a canopy [K].

This equation was used with some modifications by two different studies that computed heat transfer in green roofs [3,55]. Nevertheless, Deardorff's equation requires a lot of parameters that are not easy to assess without on-site measurements. As shown in Fig. 7, the calculated and measured sensible heat fluxes show a good agreement for forced convection conditions with all four tested models: (1) Tabares-Velasco and Srebric [11], (2) McAdams [49], (3) Logarithmic Wind Profile [48], and (4) the proposed Modified "basic model" (Equation (20)). Furthermore, the postulated modified basic method, which is the modified Newton's cooling law, provides a good agreement even for the free convection regime. To further understand this relationship, in Fig. 8, the measured sensible heat fluxes are compared to the postulated modified basic sensible heat flux model. It appears that the postulated model has a nice agreement with the measured data.

The Root Mean Square Error (RMSE) analysis is used to evaluate the error between a series of calculated and measured convective heat fluxes arranged in pairs of the same-dimension vector arrays. Giving an RMSE value is of a little value because RMSE represents a relative magnitude of the error. However, RMSE is a good method to compare different correlations among themselves, which had been commonly used in other similar studies [3,42–47]. The mean value of data recorded for the duration of the experiment was used for the calculation of the heat flux (16 values for forced convection and 10 values for free convection). Wind velocity, temperatures and other variables were measured in 1 h periods and complied into a daily average. The condition of laboratory setup is not altered during the experiment. Because of the difference between laboratory conditions of a green roof sample and open area conditions, the R^2 and the RMSE method are used.

Table 2
RMSE between calculated and measured values of sensible heat fluxes.

	Forced Convection		Free Convection	
	RMSE (W/m^2)	R^2	RMSE (W/m^2)	R^2
Number of data	16		10	
Tabares-Velasco and Srebric	23	0.52	57	0.79
Logarithmic Wind Profile	19	0.72	61	0.78
McAdams	30	0.52	13	0.87
Modified Basic	18	0.73	23	0.71

Table 2 presents RMSE and R^2 values comparison between the measured and calculated data using the Logarithmic Wind Profile, McAdams' and the postulated modified basic methods. The agreement between calculated and measured sensible heat fluxes can be considered as fairly good for all methods. In the forced convection regime, the average RMSE and R^2 for the modified basic method were about 18 W/m^2 and 0.73, respectively. However, the modified basic method gave good RMSE (23 W/m^2) and R^2 (0.71) values for sensible heat fluxes, in particular, for the free convection regime.

Fig. 9 shows the relation between the volumetric water content and air velocities. The volumetric water content exponentially decreases with days, while the air velocities do not significantly affect the volumetric water content variations. Nevertheless, in this case, the change of the volumetric water content has to be accounted for in calculations of the sensible heat fluxes. Fig. 10 shows the relationship between the volumetric water content and sensible heat fluxes. This correlation is stronger than the correlation between the temperature difference and sensible heat fluxes.

Therefore, a robust model of sensible heat transfer has to account for the effects of water content, temperature difference and air velocity at the plant level.

As shown in Fig. 10, the changing water content and temperature difference significantly affected the sensible heat fluxes, while the changing wind velocities did not show significant impact on the sensible heat fluxes for the experimental range of 0–3 m/s wind velocities. The volumetric water content exponentially decreases with the number of experimental days, while the sensible heat flux exponentially increases with the number of experimental days as observed in Fig. 10. It is observed that the sensible heat flux increases at high temperatures while the latent heat flux decreases. This correlates with the water content of the soil: if the water content of the soil decreases then the sensible heat flux increases while latent heat flux decreases, see Fig. 10a. The temperature difference between the vegetation and the air temperature increases as the water content of the soil decreases (Fig. 10b).

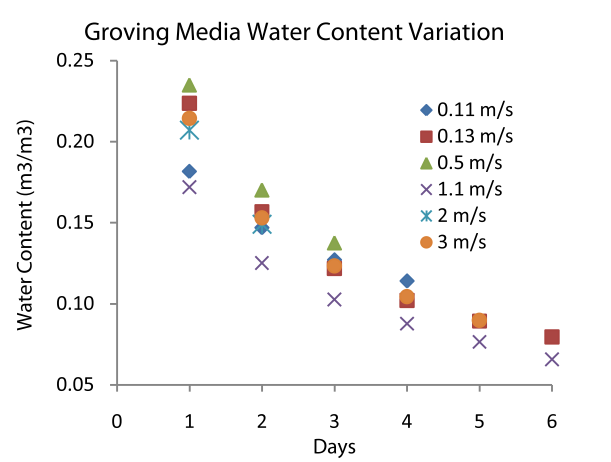


Fig. 9. Volumetric water content variations with the number of experiment days for different air velocities.

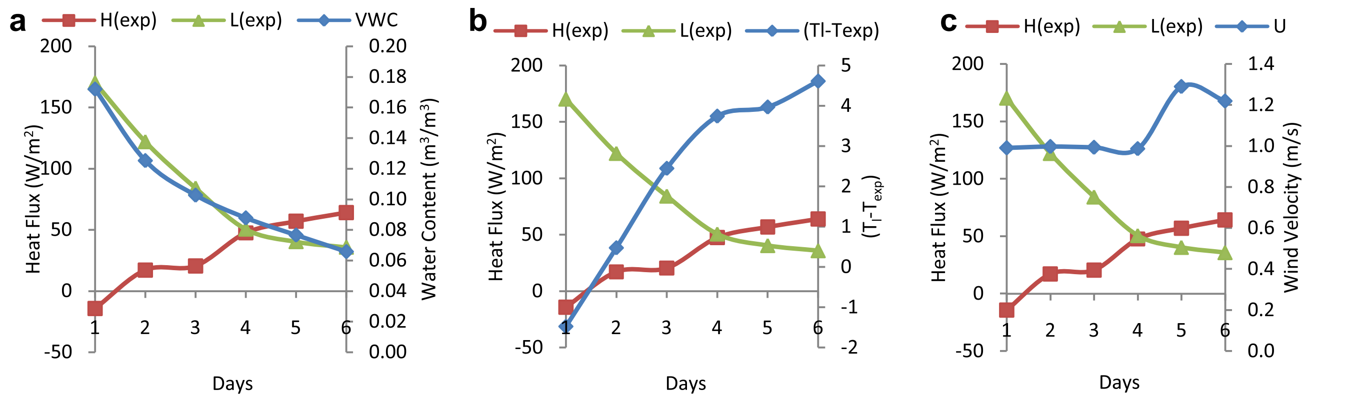


Fig. 10. Experimentally obtained heat flux variations for different wind velocities, temperature differences, and water contents.

Therefore higher temperature differences result in higher sensible heat flux while higher soil water content result in higher latent heat flux. As seen in Fig. 10c, the latent heat flux and the sensible heat flux do not change dependent upon the wind velocity. Thus, the wind velocity may be considered insignificant when calculating the latent heat flux. As the sensible heat flux increases the latent heat flux decreases and the total heat flux is stabilized.

5. Developing a model equation and discussion

Therefore, there is an inverse relationship between the volumetric water content and sensible heat fluxes, and a directly proportional relationship between the temperature difference and sensible heat fluxes. These relationships can be used to derive new equations for the calculation of sensible heat fluxes as the following:

Forced Convection,

$$H_{est} = \sigma \cdot LAI \cdot h \left(\frac{e^u}{(11 \cdot U \cdot VWC)^2} \right) \left(T_f - T_a \right)^n, \tag{22.a}$$

$n = 0$ or 1.

Free Convection,

$$H_{est} = \sigma \cdot LAI \cdot h \left(\frac{VWC}{U} e^{3VWC} \right) \left(T_f - T_a \right) \tag{22.b}$$

where VWC is the volumetric water content of the soil. Saturated water content (or VWC_{max}) for the expanded clay equal to 0.55 m^3/m^3 was obtained from a previous study [56]. These equations, (22.a) and (22.b), are modified expressions derived from a form of Equation (21) based on our measured data. A “Genetic Algorithm” software program has been used to find these equations [57]. Note that in Equation (22.a), the effect of temperature difference depends on the ‘n’ exponent. For different wind speeds (between 0 m/s and 3 m/s) and low temperature differences (for $\Delta T = T_l - T_{exp}$ between -2 °C and 5 °C) between the vegetation and air the exponent is $n = 0$. Nevertheless, for wind speeds higher than 3 m/s and for higher temperature differences, the values of the exponent ‘n’ must further be investigated. Equation (22.a) is based on laboratory data with a higher wind speed that resulted in a low temperature difference between the plants and air. This low temperature difference was due to several factors such as high wind conditions and a laboratory limitation in producing high fluxes for the short-wave radiation. As a result, the experiments with forced convection did not experience high temperatures differences. Therefore, the temperature difference did not play a major role in the convective heat transfer. Future research with instrumented green roofs installed on building rooftops will help address the validity of the ‘n’ exponent for the temperature difference when high wind conditions along with higher temperature differences are present. Fig. 11 shows a good agreement between the calculated and measured sensible heat fluxes.

Table 3 shows RMSE and R^2 value comparison between the measured and calculated sensible heat fluxes using the modified basic methods (Equation 20) and its rearranged form (Equations (22a) and (22b)). Average RMSE (11 W/m^2) and R^2 (0.81) for the rearranged (estimated) form are better than the modified basic method for the forced convection conditions. Similarly, the rearranged form of the

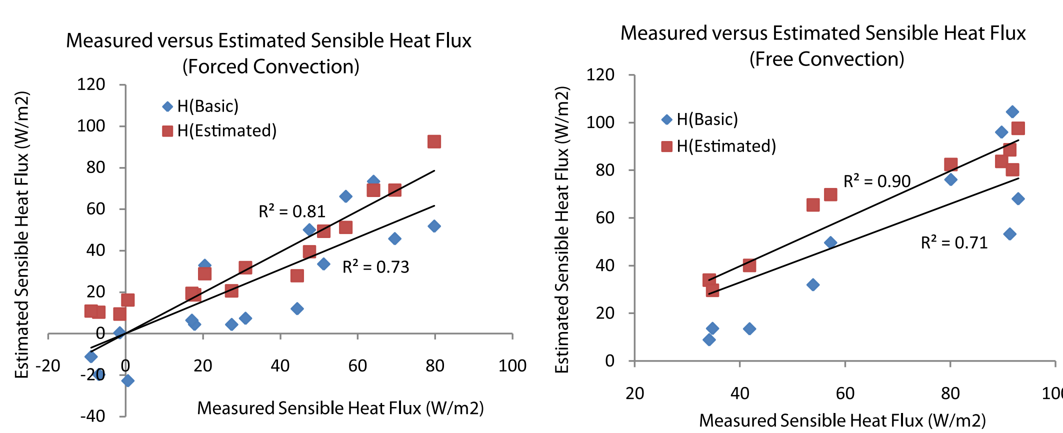


Fig. 11. The comparison between calculated and measured sensible heat fluxes for the forced and free convection.

Table 3
RMSE values for estimated and measured values of sensible heat fluxes.

	Forced Convection		Free Convection	
	RMSE (W/m^2)	R^2	RMSE (W/m^2)	R^2
Number of data	16		10	
Modified Basic (Equation (20))	18	0.73	23	0.71
Modified Basic (Equations (22.a) and (22.b)	11	0.81	6.60	0.90

modified basic method gave good RMSE (6.6 W/m^2) for the sensible heat fluxes with the free convection conditions.

6. Conclusions

This study quantified sensible heat fluxes on a green roof for different environmental conditions in a laboratory setup. In the overall heat transfer at green roof assemblies, sensible heat fluxes have a very important role, especially at the low volumetric water content (dry soil) conditions in addition to the latent heat fluxes. However, direct calculations of sensible heat fluxes and definition of a calculation method is challenging because green roofs have additional parameters, such as σ, *LAI*, and *VWC*, which significantly affect the convective heat fluxes when compared to a rectangular smooth or rough plates. These parameters change the thermal behavior of green roofs. Effects of these parameters must be understood for accurate calculations of sensible heat fluxes. Many experimental and theoretical studies examined the thermal behavior of green roofs for the outdoor environmental weather conditions. Laboratory studies were also conducted with sample plant or plants under controlled environmental conditions. Even with the controlled environmental conditions, understanding and measuring thermal behavior of plants is not easy as convective heat flux calculations require a set of highly accurate data. Nevertheless, for the stochastically-changing weather conditions, the convective heat flux correlations with wind velocities, and air and plant temperature difference, are impossible to create. Therefore, experimental green roof samples were tested in controlled laboratory conditions to create a new set of convection correlations for green roofs.

The existing literature was reviewed for available sensible heat flux correlations to include the vegetation layer in a green roof. Firstly, sensible heat fluxes were calculated from the energy balance at the green roof assembly. Secondly, a proposed modified Newton's law equation called the "basic model", as well as the Logarithmic Wind Profile model, and McAdams' model were used for sensible heat flux calculations for free and forced convection conditions. Thirdly, a rearranged form of the "basic model" was selected for further improvements due to its consistent performance in both free and forced convection conditions. The inverse ratio between the volumetric water content and sensible heat flux was observed during the laboratory measurements. This relation was used to rearrange the basic sensible heat flux calculation method for forced and free convection conditions. Effects of wind velocity and temperature difference were also considered. Equations (22.a) and (22.b) give the newly proposed form of Newton's cooling law for calculation of sensible heat fluxes to/from a green roof. A good agreement was observed between the calculated and measured sensible heat fluxes. For the forced convection flow regimes, the convective heat flux calculations with the proposed "basic model" resulted in an average RMSE and R^2 values of 11 W/m^2 and 0.81, respectively. Similarly, the proposed basic sensible heat flux model provided good RMSE (6.6 W/m^2) and R^2 (0.90) values for sensible heat flux with free convection conditions. In the future, this model will be used in on-site experimental studies to understand its performance under wind conditions that exhibit a much wider range than the studied 0–3 m/s wind velocities near the leaf canopy.

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