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Utilizing a novel mobile diagnostics lab to validate the impact of vegetative wall coverings in building cooling load reduction

To cite this article: O Fagbule *et al* 2021 *J. Phys.: Conf. Ser.* **2069** 012126

Utilizing a novel mobile diagnostics lab to validate the impact of vegetative wall coverings in building cooling load reduction

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Abstract. Building cooling loads are driven by heat gains through enclosures. This research identifies possible ways of reducing the building cooling loads through vegetative shading. Vegetative shading reduces heat gains by blocking radiation and by evaporative air cooling. Few measured data exist, so we gathered thermal data from a vegetative wall grown in front of a Mobile Diagnostics Lab (MDL), a trailer with one conditioned room with instrumentation that collects thermal data from heat flux sensors and thermistors within its walls. In spring 2020 a variety of plants were cultivated in a greenhouse and planted in front of the south façade of the MDL, which was placed in direct sunlight to collect heat flux data. The plants acted as a barrier for solar radiation and reduced the amount of thermal energy affecting the trailer surface. Data were collected through the use of 16 heat flux sensors and development of continuous infrared (IR) images indicating surface temperature with and without plant cover. The façade surface beneath the plants was 10-30 °C cooler than exposed façade areas. In further analyses, the heat-flux data were compared to IR temperature data.

1 Introduction

This paper presents a validation of the impact of vegetative wall coverings on building cooling load reduction. Building surfaces gain and lose heat through four major processes of energy transfer: Radiation, conduction, convection and evaporation. The zones of the building interior, the exterior walls and roof, and the interior building environment are where heat gain and loss occur. Radiation is the primary source of heat gain, where direct and indirect solar radiation are the most important sources. Reflected solar radiation and thermal radiation are also significant. Direct heat gain occurs within a building, specifically on the walls and roof areas, whereas indirect heat gain occurs in the surrounding exterior environment. Radiant energy is transmitted to the building interior through transparent openings in the building such as windows. Radiant energy is also transmitted through the exterior walls and roof by the energy absorbed at the surface and conducted to the interior.

Vegetative walls and façades have always been known for preventing heat gain and encouraging cooling load reduction. For heat gain prevention they work by shading the building and surrounding surfaces, blocking radiation reflected or radiated from surrounding surfaces, and by blocking hot winds. Plant can also act as insulation to reduce heat loss.

To enhance heat loss in warm or hot seasons, plants direct and increase the velocity of cool breezes and reduce air temperature of the surrounding environment through evapotranspiration. Vegetative walls are effective mainly due to evapotranspiration. Evapotranspiration provides cooling effects, as water is evaporated from the soil and plants and plants transpire by taking water in through roots which is then released through the leaves. The energy from the sun that would otherwise heat the wall surface and increase ambient air temperatures is instead used for the evapotranspiration process. This process results in latent heat loss that lowers surrounding air temperatures. The research was conducted by growing plants on the south façade of a Mobile Diagnostic Lab (MDL) which is equipped with heat flux sensors, Figure 1. For the project presented in this paper, the vegetative wall was grown with a support system in front of the southern wall of the MDL. This structure created a gap between the wall and the plantings as shown in Figure 2, allowing air to move up by convection through the space between the wall and the vegetation providing passive cooling of the outside surface.

Research on methods of passive building cooling has been ongoing for some time [1], [6]. Significant data exists for green roofs, which have been proven useful, but limited data exists to quantify the impact of vegetative wall coverings. In order to improve design predictions for including vegetative coverings, current input assumptions need data for validation and to enable the integration of green walls in energy simulation and design prediction. The purpose of this study is to add quantifiable data to existing tacit knowledge that plants near wall surfaces can function to reduce cooling loads on building surfaces.

2 Methodology

The Mobile Diagnostics Lab (MDL) shown in Figure 1, served as the major device for the experiments. Plants were added along the south façade of the MDL in the summer of 2020. The trailer has one window located on the north and another window located on the south façade. The MDL is equipped with 16 heat flux sensors and 16 thermistors.

Figure 1: Mobile Diagnostic Lab (MDL)

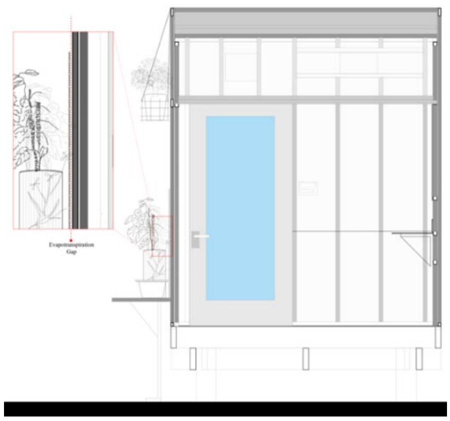

Figure 2: MDL section with plants

2.1. Mobile Diagnostics Lab Description

The MDL in Figure 1, is designed to be versatile to conduct different building energy research applications and is owned by the Iowa State University Centre for Building Energy Research. It is composed of a 2.5m (W) × 3.0m (L) × 2.7m (H) experimental cabin and an attached mechanical room which are mounted on a 5.8m-long trailer with air suspension. The MDL envelope is built to be air-tight, and part of the wall section assembly is interchangeable. It houses a programmable HVAC system and an expandable data acquisition system (DAS). The DAS can collect data at different frequencies with multiple sensors and provide real-time data with remote access. Currently, about 250 data measurement points are wired in the MDL, collecting data on air temperature and humidity inside the experimental cabin, surface temperature and heat flux inside and outside the experimental cabin, power generation, and gas consumption. The research capacities of the MDL enable studies of diverse heat transfer paths through different building materials and between building surfaces and ambient conditions, as well as PV power system efficiency, baseline energy consumption for different climates, and CFD models for natural ventilation and passive heating. For this study 16 heat flux sensors and 16 thermistors were used.

2.2. Plants

Planning and planting for the vegetative wall began in February 2020. The plants were grown in a school greenhouse. We started clematis, tomato sakura (grape tomatoes) and virginia creeper. These plants were cultivated from seeds till they were fully grown plants, then arranged on the south façade of the MDL on May 27th, 2020 as shown in Figure 3. Plants were watered and tended regularly every two to three days.

In June, American plum and downy serviceberry shrub seedlings (1-7 plants) were added to the other plants in Figure 4. For additional plant cover on the south façade during late summer we added Chinese wisteria, and more vine plants for surface coverage. These were placed at the top of the south façade in Figure 5. The plants were removed on October 19th, 2020, at the end of the growing season.

Figure 3: MDL, May 2020.

Figure 4: MDL, June 2020

Figure 5: MDL, July 2020

2.3. Infrared Images and Analysis Methods.

The infrared images were taken with a Flir infrared camera (model number: T6406x, resolution: 480 x 640 (DPI) that took both infrared images and photographic images. These pictures were taken every two days between 11am and 2pm. The emission was set to 0.77 units here based on the exterior surface material, grey aluminium sheathing. The images were taken at 4.5m distance from the front of the trailer and included areas directly in sun and areas affected by the shading and evaporative cooling of the plants. The images were analysed using the Flir tools app that provided surface temperatures at different points of the façade. Analysis was done to compare temperatures of surfaces with plant cover to those that did not. The photographic images clearly show the extend of shading and the porous leaf area of the plants less than 100% as shown in Figure 6 & Table 1.

Figure 6: MDL Infrared image analysis points

Table 1: MDL Infrared analysis points

Point	**Information**
F1	Façade surface one: Temperature data from Flir camera trailer surface
F2	Façade surface two: Temperature data from Flir camera for trailer surface
P1	Plant surface one: Temperature data from Flir camera for trailer surface behind plants
P2	Plant surface two: Temperature data from Flir camera for trailer surface behind plants

Surface temperatures were also analysed by calculating the sol-air temperatures of the south façade wall. This temperature is the result of the combined effects of the actual outdoor temperature distribution plus incident solar radiation, formula in Equation 1. For further analysis of the IR temperature, the values of F1 and F2 were averaged to obtain the values for Fav, while the values for P1 and P2 were also averaged to get Pav. These values were used in the comparison to the calculated sol-air temperature. The air temperature measured at nearby weather stations [10][11] was recorded for the day by the hours the picture was taken (11am to 2pm). These values were averaged to get an accurate air temperature of when the pictures were taken. These were used in the Sol-air analysis in Section 3.2.

Equation 1: Sol-Air Temperature.

$$t_e = t_o + \frac{\alpha l}{h_o} - 3.9°\text{C}$$

Where
t_e = Sol-air Temperature
t_o = Outdoor (ambient) Temperature
α = absorptance of surface for solar radiation (0.5 used for a grey surface)
l = Total solar radiation incident on the surface (W/m^2)
h_o = Coefficient of heat transfer by long wave radiation and convection at the surface (Usually assumed to be 17W/m^{2}k)
3.9°C is the constant for horizontal surfaces that receive long-wave radiation from the sky, 0°C for vertical surfaces.

2.4. Sensor Data Collection Methods

2.4.1 CR 1000 data logger. The data collected in the Mobile Diagnostic Lab (MDL) is stored in a CR1000 datalogger (Campbell Scientific, Logan, Utah). Data are collected from a set of 16 heat flux sensors and 16 thermistors placed in the MDL. Sensors are placed near each corner of three side façades and the roof. One of the side façades does not have sensors because of the location of the door and systems installed on the other side of that façade (it is considered adiabatic). Data available for analysis are from 15th Sep. 2020 to 15th Dec. 2020. Data were collected and stored every minute in the datalogger from 15th Sep. to 16th Oct. and every fifteen minutes from 15th Oct. to 15th Dec.

2.4.2 EnergyPlus software input data preparation. For uniformity of the data set and for further studies, data were averaged to represent the top of the hour for each hour. This was chosen so that data can be used in further studies by other researchers in the university and to allow data to be used in the EnergyPlus software (US DOE 2021) [9], which requires data to be in an hourly format.

2.4.3 Interpolation. Given the volatility of weather and the fact that the datalogger was powered by a single PV array, some data gaps occurred. To fill the gaps for missing data we used an interpolation method. The FORECAST.ETS formula from Microsoft Excel [3] was selected, because it predicts the next values by looking at graphical trends from previous values and because the data gaps were large and simple interpolation would not have followed the graphical trend.

2.5. R-value
The R-value data were collected using the Arduino-based data logging system by fluxteq (Blacksburg, VA). The data were collected during the afternoon of 3rd Sep. 2020 for fifteen minutes. We used short-term data for this because the R-value remains constant for any material in all weather conditions.

2.6. Heat Flux Analysis
The heat flux sensors measured data over time overlapping with the infrared temperature data. The heat flux results were analysed both for direct comparison shown in Figure 10 and calculation. The heat flux for the façade surface with plants [HF(P)] and the façade surface without plants [HF(NP)] were calculated using temperature difference multiplied by the R-value (1/U). The R-value used in the calculation is 1.0797 (U-value is 0.92618), which was the average taken from an R-value sensor test done in September. The temperature difference (ΔT) was calculated from the outdoor temperature and the average of the generated surface temperatures with plant cover and no plant cover (Fav and Pav). These values were used in Equation 2 to calculate for the heat flux.

Equation 2: Heat flux and Cooling load

$$Heat\ flux = \Delta T * U$$
$$Cooling\ load = \Delta T * U * A$$

3 Results
Results are reported here for infrared images (Section 3.1), surface temperature analysis (Section 3.2), comparison to sol-air temperature analysis (Section 3.3), and by calculation and heat flux analysis (section 3.4). Cooling loads were also calculated and analysed (section 3.5).

3.1 Infrared Images
The infrared images illustrate effects of the plant cover on the south façade of the MDL. The series of images shown in Figures 7a to 7f, are from the time when the plants were placed outside the MDL to the end of the growing season.

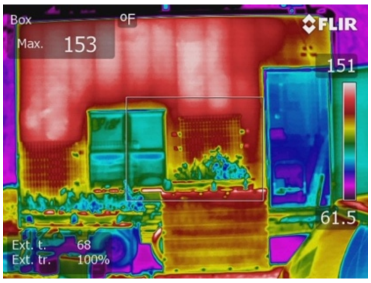

Figure 7a: MDL, May 2020.

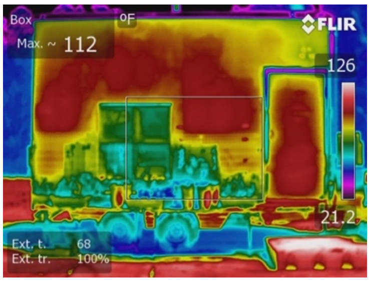

Figure 7b: MDL, June 2020

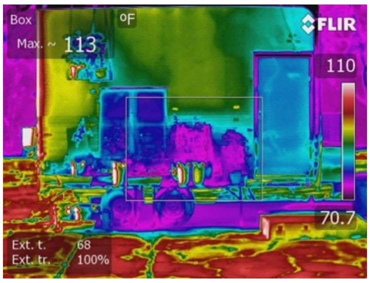

Figure 7c: MDL, July 2020

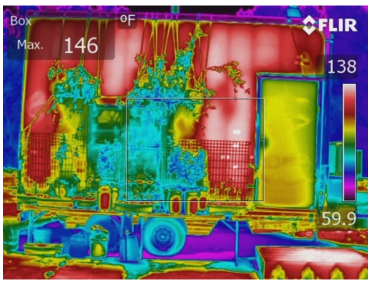

Figure 7d: MDL, August 2020.

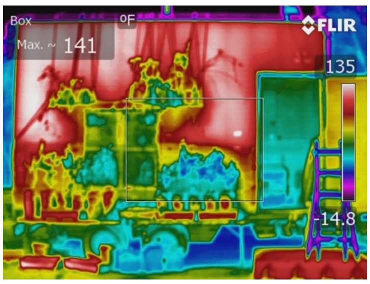

Figure 7e: MDL, September 2020.

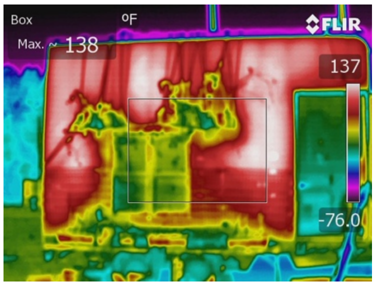

Figure 7f: MDL, October 2020

3.2 Surface Temperature Analyses
Data were collated from the points listed in Figure 6 and Table 1. Temperature differences between 10-30 degrees Celsius were detected between the surface temperatures of building surfaces with plant cover compared to surface temperatures in areas without plant cover. From May through October temperatures were consistently lower for areas of the façade with plant covering in Figure 8, This data set was compared, the analysis points in Table 1 and Figure 6, with values in the infrared photographs taken from 11am to 2 pm every other day. There are some outliers in this data set that are due to the volatility of the weather.

Figure 8: Surface Temperature Direct Comparison Analysis (F: Façade Surface, P: Plant Surface)

3.3. Sol-air Temperature Analysis
The calculated sol-air temperature is consistent with measured value of Fav (some outlier data points occurred likely due to cloud cover, while the data for Pav remained at least 5-10 degrees C lower than the calculated sol-air temperature and the data for Fav in Figure 9. The air temperature values are only slightly lower than the average surface temperature with the plants. The leaves of the plants do not fully shade the MDL in Figure 6, so this is to be expected.

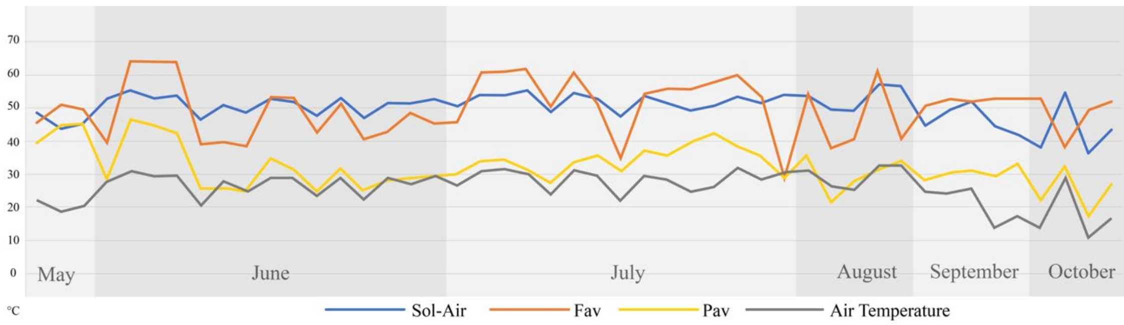

Figure 9: Sol-Air analysis (Fav: Façade surface temperature average, Pav: Plants surface temperature average)

3.4. Heat Flux
The calculated heat flux without plant cover [HF(NP)] is higher than the one with plant cover [HF(P)]. The values from the measured heat flux sensors (they are located in the interior of the trailer) are shown as [HF(M)] in Figure 10. The measured values from heat flux sensors [HF(M)] are lower than the calculated values form the surface without plant cover [HF(NP)].

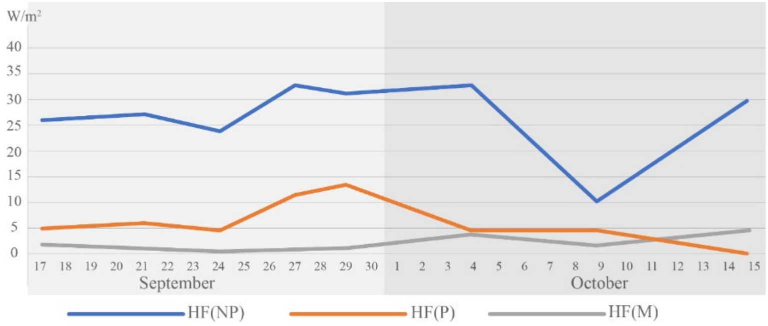

Figure 10: Heat flux direct comparison

3.5. *Building Cooling Load*

The results from the heat flux calculations were then used to find values for cooling load as shown in Figure 11. The building cooling load was calculated per Equation 2, using the area (A) of the south façade of the trailer (about $8.2m^2$)· The cooling load for the façade surface that does not have plant cover [CL(NP)] and the façade surface with plant cover [CL(P)] were compared in Figure 11. There is a reduction of 45-250W in cooling loads for surfaces that have plant cover (with the exception of a data outlier on October 9^{th}, as noted before due to unusual weather conditions).

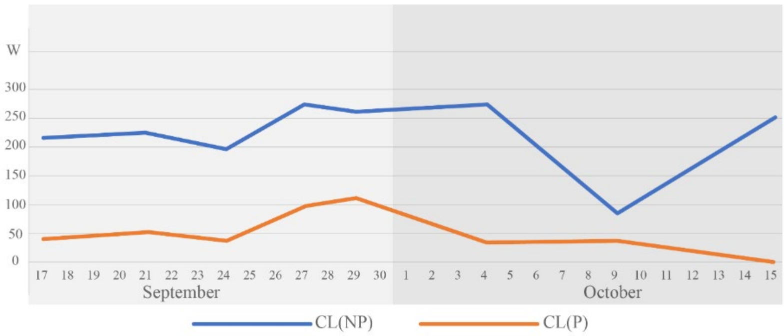

Figure 11: Cooling Load

4 Discussion

Our experimental research was successful in obtaining measured data from the heat flux and thermistor sensors and infrared images and compare those with calculated sol-air temperature data. The data derived from infrared images showed a temperature difference of 10-30 °C for surfaces with plant cover even if the plant cover was not 100%. This study produced the finding of a 45-250W reduction in the building cooling load in Figure 11. The calculated heat flux for the surface with plant cover [HF(P)] and without plant cover [HF(NP)] also shows the heat flux reduction inside of the MDL. The location of the research is a place with volatile weather which caused some spikes in the data, especially on October 9^{th} in Figures 10 and 11. The limitations of the heat flux analysis were that only two months (September and October) of data for both heat flux sensors and infrared images were considered and images were only taken around the noon hour, thus a whole growing season and finer daily timesteps should be analysed next. The next challenge is to assess the percentage of solar radiation blockage versus evapotranspiration in effecting the surface temperature of the MDL. Several variables need to be considered to accomplish this in the next series of measurements: the leaf area index, which influences the solar radiation blockage, the time lag of the surface heat flux based on the materiality and the actual evapotranspiration rate of the plants themselves, which in turn is influenced by air temperature. The challenge Another limitation of the study was that the research team did not calculate the amount of water needed to keep the plants growing on the southern façade. Water use for evapotranspiration should be accounted for in future studies to enable transferability to regions with less precipitation.

5 Conclusion

Our study contributes experimentally measured cooling load reduction data for vegetative wall coverings using a mobile diagnostics lab system to collect empirical data. Further studies will include use of more diverse sets of plants and their placement in different locations. The data collected will be used to build an energy model for the MDL in order to develop a novel heat transfer coefficient for plants. This can then be made available to designers to create vegetative walls and for further studies regarding the potential for vegetative wall coverings to reduce the urban heat island effect, a specific challenge in this study location.

References

[1] Spirn, A., Santos, A., Johnson, D., Harder, L., & Rios, M. (1981). Plants for passive cooling. a preliminary investigation of the use of plants for passive cooling in temperate humid climates. doi:10.2172/5450077

[2] O'Callaghan, P., & Probert, S. (2003, August 08). *Sol-air temperature*. Retrieved February 27, 2021, from https://www.sciencedirect.com/science/article/abs/pii/0306261977900174

[3] Forecast.ets function. (n.d.). Retrieved February 27, 2021, from https://support.microsoft.com/en-us/office/forecast-ets-function-15389b8b-677e-4fbd-bd95-21d464333f41

[4] McGuinness, W. J., Stein, B., Grondzik, W. T., Kwok, A. G., & Reynolds, J. S. (1964). *Mechanical and electrical equipment for building* (11th ed.). New York, New York: Wiley.

[5] Connor, N. (2019, June 04). What is Fourier's law of thermal Conduction - definition. Retrieved February 27, 2021, from https://www.thermal-engineering.org/what-is-fouriers-law-of-thermal-conduction-definition/

[6] Palmer, L. (2017). Adding power to the value of trees. *Nature Energy, 2*(4). doi:10.1038/nenergy.2017.20

[7] Subedi, A., & Chávez, J. L. (2015). Crop evapotranspiration (et) estimation models: A review and discussion of the applicability and limitations of et methods. *Journal of Agricultural Science, 7*(6). doi:10.5539/jas.v7n6p50

[8] Flir tools. (n.d.). Retrieved February 27, 2021, from https://www.flir.com/products/flir-tools/

[9] EnergyPlus. Accessed May 28, 2021. https://energyplus.net/.

[10] Daryl Herzmann. Department of Agronomy, Iowa State University "IEM :: Download ASOS/AWOS/METAR Data." Iowa Environmental Mesonet. Accessed May 28, 2021. https://mesonet.agron.iastate.edu/request/download.phtml.

[11] US Department of Commerce, NOAA. National Weather Service. NOAA's National Weather Service. Accessed May 28, 2021. https://www.weather.gov/.

Acknowledgements

This work is supported by the National Science Foundation, Award # 1855902. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. The authors would also like to thank Mike Wassmer (Live to Zero LLC) for continued support with our data acquisition systems.