GREEN COOLING: COMBINING VEGETATED ROOFS WITH NIGHT VENTILATION

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ABSTRACT

This paper describes the effects of green roofs and night ventilation on internal temperature of buildings using test cells with different configurations. Three cells are used in these tests, all of them cooled with night ventilation, one with an insulated green roof, another with an uninsulated green roof and another with a conventional code compliant insulated roof.

Several series are performed and results indicate that the test cell with the green roof and no insulation performs better than the test cell with the insulated green roof and the conventional insulated roof. Thus, in warm climates with cool nights, when it is possible to use night ventilation to passively cool a building, it is preferable to have the soil mass coupled with the inside of the building instead of having additional insulation separating this mass from the space. Equations are derived from the experimental work that permit to calculate internal maximum temperatures as a function of outdoor maximum and mimimum temperatures with different glazing to floor ratios.

1. INTRODUCTION

A living or green roof is a roof that is substantially covered with vegetation. Such a strategy has been proven to have positive effects on buildings by reducing the stress on the roof surface, improving thermal comfort inside the building (1), reducing noise transmission into the building, reducing the urban heat island effect by reducing “hot” surfaces facing the sky, reducing storm water runoff, re-oxygenating the air and removing airborne toxins, recycling nutrients and providing habitat for living organisms while creating peaceful environments.

The positive thermal effects of green roofs are usually described by a) the reduction of the external surface temperature by the regulating effect of the vegetation, and b) the reduction of the thermal transmittance of the assembly, mostly due to the effects of insulation, usually placed between the earth or sustaining material and the interior space of the building. Most of the cooling effects that a planted roof can provide , apart from providing protection against overheating, are related to evaporation (4). Their vegetative matter absorbs solar radiation through the biological processes of photosynthesis, respiration, transpiration, and evaporation. However, the solar radiation that bypasses these processes can seep into the building envelope (5).

Studies have demonstrated that a well planned and managed green roof acts as a high quality insulation device in the summer (2). But little has been done to take advantage of the mass of the green roof as a heat sink in temperate or hot climates. By reducing daily thermal fluctuations on the outer surface of the roof and increasing thermal capacity in contact with the indoors, green roofs can contribute to the cooling of spaces with lower energy consumption during warmer weather if the mass of the soil is cooled, especially if it is cooled by a passive strategy such as night ventilation. There has been some research in this direction that indicates potential to reduce the cooling loads inside buildings (3).

Nocturnal ventilative cooling occurs when an insulated high-mass building is ventilated with cool outdoor air so that its structural mass is cooled by convection from the inside, bypassing the thermal resistance of the envelope. During the daytime, if there is a sufficient amount of cooled mass and it is adequately insulated from the outdoors, it will act as a heat sink, absorbing the heat penetrating into and generated inside the building, reducing the rate of indoor temperature rise. This ventilation system can be either fan forced or natural through windows that are opened and closed at appropriate times. During overheated periods the ventilation system (windows or fans) must be closed to avoid heat gains by convection. Nocturnal ventilative cooling is a well known strategy that has been used for many years, mostly in warm and dry climates (6).

The main parameters that determine the efficiency of night-ventilation can be classified in three broad groups: climatic parameters, building parameters and technical parameters of the technique (7). Combining night ventilation with green roofs should provide adequate cooling in climates with appropriate conditions.

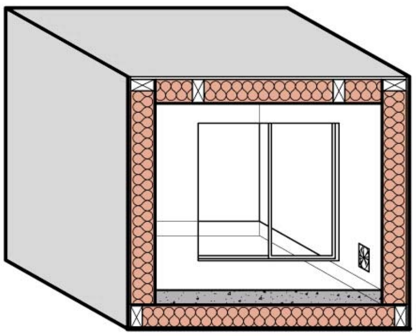

Fig. 1: Control Cell simulating a lightweight building

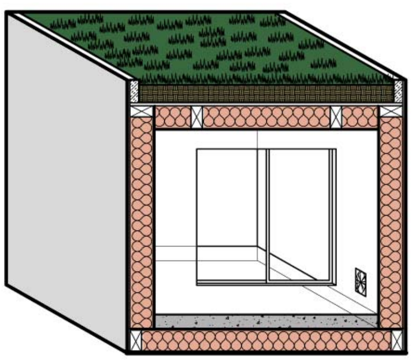

Fig. 2: Cell with the insulated green roof.

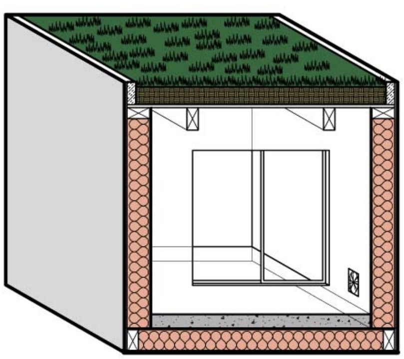

Fig. 3: Cell with the uninsulated green roof.

2. EXPERIMENTAL SYSTEM

This paper discusses the effect of using night ventilation for space cooling in buildings with uninsulated and insulated green roofs, and the effects of different window sizes on the internal temperature (Figs 1,2,3). Five test cells were built by the author and Architecture and Master of Science in Regenerative Studies students in the Lyle Center for Regenerative Studies at Cal Poly Pomona to study the performance of different types of passive cooling systems (Fig 4 &5).

Figure 4: Construction of the Test Cells at the Lyle Center

All test cells have an external dimension of 1 x 1 x 1 meters and are built using stud wall construction with 2” by 4” studs, drywall on the inside, plywood on the outside and batt insulation in between for a U value of 0.12 W /m^2 K in the walls and 0.055 W /m^2 K in the roofs. Exterior is painted white and all have 2ft by 2ft single glazed windows facing south. All of the cells are equipped with fans controlled by dimmers and timers that can adjust the operation and intensity of ventilation.

All of the cells have 1 ½” (0.038 m) thick concrete pavers as the slab. In the uninsulated green roof, the soil is thermally coupled with the interior through a metal plate, while the other cell has 4” (0.1 m) of matt insulation between the space and the soil.

Figure 5: The five test cells at the Lyle Center

The effects of modifying the window dimension and the insulation level of the cells is compared in three series: 4 ft^2 (0.37 m^2) window, 2 ft^2 (0.165 m^2) window ,and no window. Temperature is measured with thermistors in the center of the space and in the surface of the conventional roof and the exposed roof, and recorded every ten minutes in a data logger.

Fig. 6: The green roof.

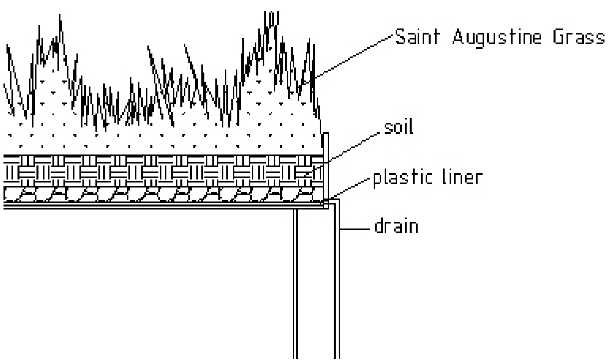

Fig. 7: Detail of the green roof.

The green roofs are of the extensive type. They are covered with Saint Augustine grass (Fig. 6) above a layer of soil 3 inches thick with an inch of gravel and a plastic liner underneath (Fig 7.). Drainage tubes are spread through the gravel with perforations that capture the excess water and drain it outside the building. The plastic liner is spread above a metal plate that is supported by wooden joists. The metal plate assures thermal coupling between the mass and the space underneath (Fig 2). In both the insulated roof and the uninsulated green roof, gypsum board is placed beneath the wood joists to hold the batt insulation that decouples the mass of the soil with the interior space (Fig 3).

3. EXPERIMENTAL RESULTS

The climatic parameters that determine the effectiveness of nocturnal ventilative cooling are the minimum air temperature, which determines the lowest temperature achievable inside the building; the daily temperature swing, which determines the potential for lowering the indoor maximum below the outdoor maximum; and the water vapor pressure level, which determines the upper temperature limit of indoor comfort with still air or with air movement (8). During the measurement period night temperatures and relative humidity were sufficiently low for nocturnal ventilative cooling and all three cells have a timer that sets the fan set to operate from 9 PM to 5 AM at 25 air changes per hour.

TABLE 1: Maximum Temperatures

Series Number & Name	Out-door	Control Cell w night vent	Green Roof Insula-ted	Green Roof no Insula-tion
Series 1: Window / floor ratio 25%	24.5	34.9	32.1	29.0
Series 2: Window / floor ratio 12.5%	22.0	26.8	25.2	23.2
Series 3: No window	25.5	24.8	22.9	21.9

3.1 Series 1: 100% window

In this series initiated September 7, 2005, the window is 4 ft^2 (0.37 m^2) in area or 25% of the floor area. Temperatures in all three cells are always higher than outdoor, especially during the daytime, due to the solar gain through the windows of the control cell. (Fig. 8). The values of the maximum temperature in the control cell are an average of 10.4 °C above the outdoor temperatures and in the insulated green roof they are 7.6 °C above the outdoor temperatures, in the uninsulated green roof they are 4.5 °C above the outdoor temperature.

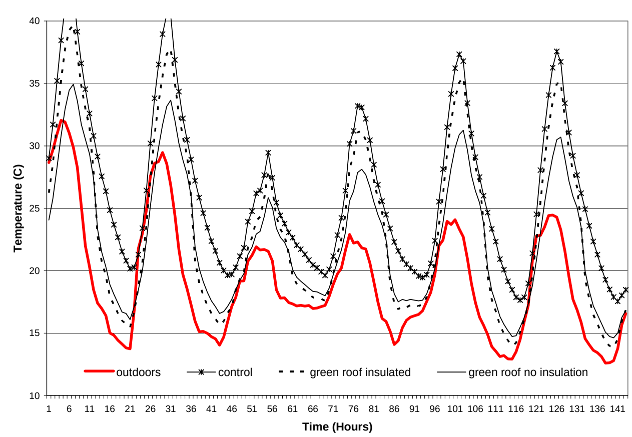

Fig. 8: Series 1: 100% window, glazing to floor ratio 25%

3.2 Series 2: 50% Window

In this series initiated September 7, 2005, the window is 2 ft^2 (0.185 m^2) or 12.5% of the floor area. During the day, the values of the maximum temperatures in the control cell are an average of 4.8 °C above the outdoor temperature, in the insulated green roof they are 3.2°C above the outdoor temperatures, in the uninsulated green roof they are 1.2 °C above the outdoor temperature. Because the glazing to floor ratio is smaller, the difference between the maximum temperatures inside all cells and the outdoor maximum temperature is less than in the previous series (Fig. 9).

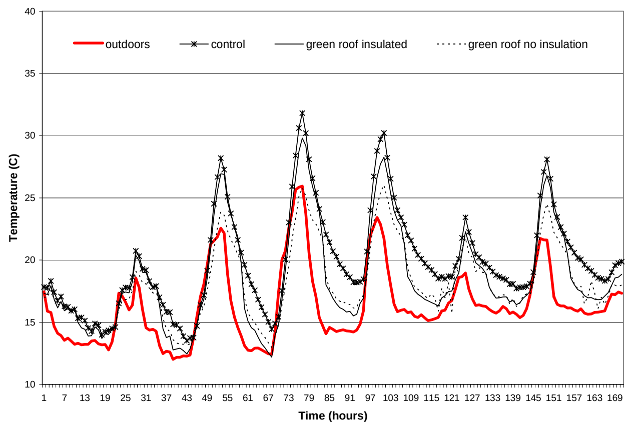

Fig. 9: Series 2: 50% window, glazing to floor ratio 12.5%

3.3 Series 3: No window

In this series initiated September 7, 2005, there is no window. During the day, the values of the maximum temperatures in the insulated control cell are an average of 0.7 °C below the outdoor temperature, in the insulated green roof they are 2.6 °C below the outdoor temperature, in the uninsulated green roof they are 3.6 °C below the outdoor maximum temperature.

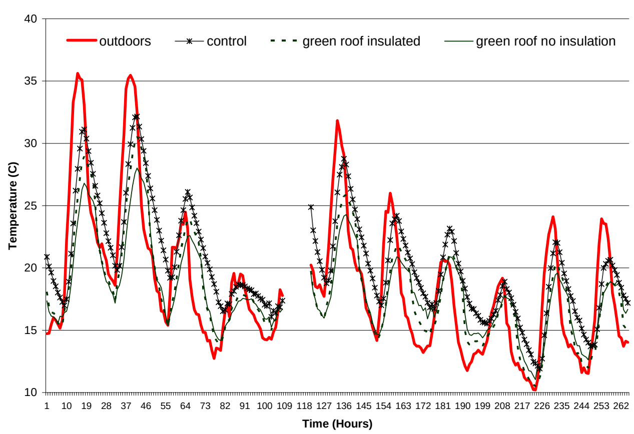

Fig. 10: Series 3, No window.

Because there is no solar gain through the windows and all cells are insulated and night ventilated, the maximum temperature inside all cells is lower than the maximum temperature outdoors, with the largest difference in the uninsulated green roof. (Fig. 10).

4. DISCUSSION

Two variables are used to evaluate the performance of the three series: the maximum average temperatures and the temperature difference ratio (TDR).

4.1. Differences of the Maximum Average Temperatures

The difference between the average maximum temperatures in the three cells is indicative of the performance of the system. The lower the average maximum temperature and the larger the difference between the maximum averages in the cells, the better the performance.

TABLE 2: Differences in the maximum average temperatures

Series	Control Cell	Green Roof Insulated	Green Roof Uninsulated
Series 1: Window / floor ratio 25%	10.4	7.6	4.5
Series 2: Window / floor ratio 12.5%	4.8	3.2	1.2
Series 3: No window	-0.7	-2.6	-3.6

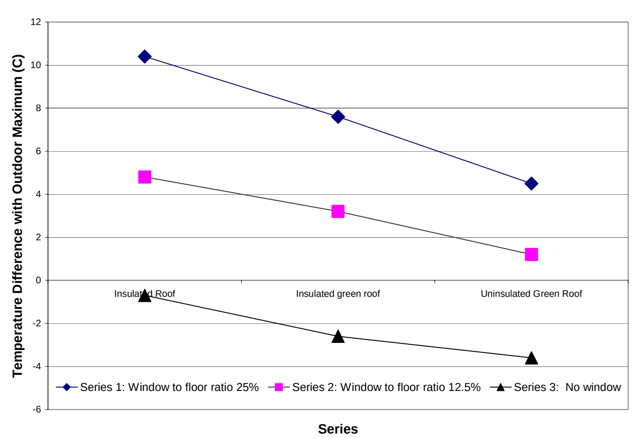

Fig. 11: Differences in maximum temperatures

In all of the series the green roof without insulation has a lower average maximum temperature than the other cells. As the window size is reduced, the difference between the maximum temperature inside all the cells and the outdoor maximum temperature is also reduced. Only when the window is eliminated is the indoor maximum temperature in the test cells lower than the outdoor maxim.

4.2. Temperature Difference Ratio

The three tests are compared with each other using the Temperature Difference Ratio, TDR. This concept was proposed by Givoni and used with good results to compare passive cooling systems with different configurations (10) (6)TDR is calculated using the following equation:

$$TDR = (T_{maxout} - T_{maxin}) / (T_{maxout} - T_{minout}) \qquad (1)$$

Where:
TDR= Temperature Difference Ratio
T_{maxout}= Maximum temperature outside
T_{maxin}: Maximum temperature inside
T_{minout}: Minimum temperature inside

In a naturally ventilated building the TDR can't be higher than 1.0 and the resulting fraction can be expressed as a percentage. The higher the value (closer to one) of the TDR, the better the cooling performance of the system. A higher value indicates that there is a larger temperature difference between outdoors and indoors and that there is more cooling. A negative value indicates that the average maximum temperature inside the test cell is higher than outdoors. The TDR concept normalises the capacity to reduce the indoor maximum temperature, as a function of the outdoor swing, permitting comparison of the different series. TDR is calculated for the different series and averaged for all the days in each series (Table 3). The best TDR in the experimental cell is in series 3, which performs much better than the other cells in each series (Fig 12).

TABLE 3: TDRs FOR THE DIFFERENT SERIES

Series	Control Cell	Green Roof Insulated	Green Roof Uninsulated
Series 1: Window / floor ratio 25%	-1.021	-.75	-.442
Series 2: Window / floor ratio 12.5%	-.57	-.375	-.141
Series 3: No window	0.067	0.233	0.323

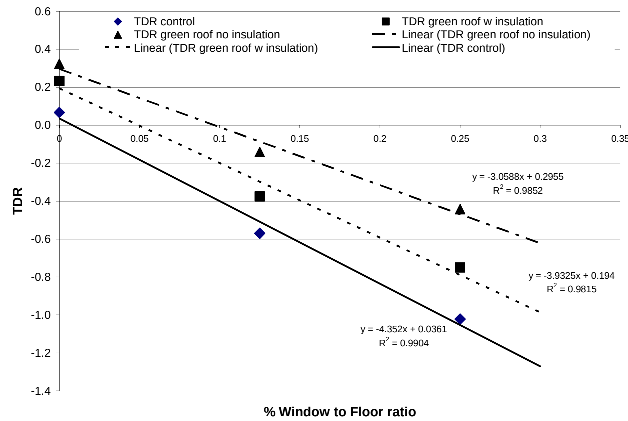

Fig. 12: TDR as a function of the window to floor ratio

The equations that predict TDR as a function of the floor to window ratio (FWR) are:

For the control cell:

$$TDR = -4.352*FWR + 0.0361 \qquad (2)$$

In equation (2) $R^2 = 0.99$

For the green roof with insulation:

$$TDR = -3.9325*FWR + 0.194 \qquad (3)$$

In equation (3) $R^2 = 0.98$

For the green roof without insulation:

$$TDR = 3.0588*FWR+0.2955 \qquad (4)$$

In equation (4) $R^2 = 0.98$

After TDR is calculated for a building using equations 2, 3, and 4 it is possible to predict the indoor maximum temperature using equation (1) and solving for T_{maxin}

$$T_{maxin} = T_{maxout} - [TDR * (T_{maxout} - T_{minout})]$$

Where outdoor maximum and minimum temperatures, or daily temperature swing, must be known. These equations would be valid in buildings with slab on grade concrete floors with a thickness of 1.5".

5. CONCLUSION

A green roof can help cool a space in two ways: the top of the green roof that faces the exterior -where the plants are- reduces the effect of solar gains by reducing the sol-air temperature, and the interior acts as a thermal mass, that is cooled at night and acts as a heat sink during the day.

Results indicate that the test cell with the green roof and no insulation performs better than the test cell with the green roof with insulation and the conventional insulated roof, This indicates that in warm or mild climates with cool nights it is preferable to have the soil mass coupled with the inside instead of having additional insulation reducing external solar gains. The vegetation at the surface of the green roof blocks solar gains permitting the thermal mass to better work as a heat sink for the interior of the space.

Simple equations are derived from the experimental work that permit to calculate internal maximum temperatures as a function of outdoor maximum temperature and daily swing, for the uninsulated green roof and the insulated green roof with the different window dimensions expressed as glazing to floor ratios.

Green roofs, can lead to more comfortable conditions inside buildings, with increased energy efficiency. But even if this improvement in performance only occurs when it is possible to cool the internal mass, maybe using strategies such as night ventilation, this should give added value to green roofs increasing their applicability.

More series should be performed under more extreme conditions to determine the applicability limits of this combination and the how these limits vary with different amounts of mass. Until these series are performed it is probably safe to assume that the applicability zone should be similar to that indicated in Givoni and Milne's chart (Fig 13).

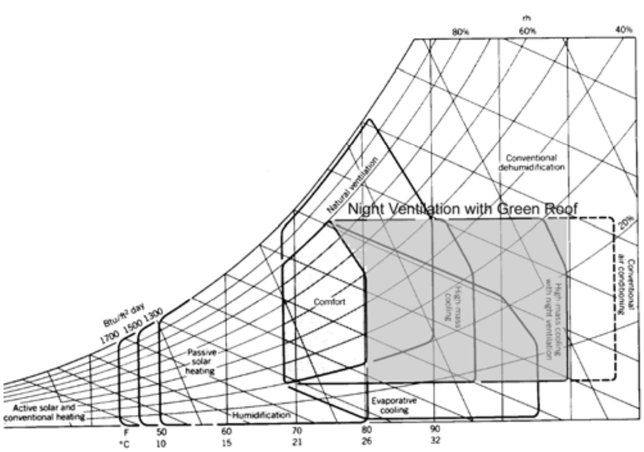

Fig. 13: Applicability of night ventilation with green roofs.

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