A Study on the Insulation Effect of the Roof Greening Overhead Structure in Hot-moist Regions

Xueli Jin*, Yongping Hu¹, Guiting Zhou¹, Zhilu Huang¹, Rongying Li¹, and Qinglin Meng²

¹Guangzhou Panyu Polytechnic, Guangzhou, 511483, China
²State Key Laboratory of Subtropical Building Science, South China University of Technology, Guangzhou, Guangdong, 510640, China

*Correspondence: 710652805@qq.com; Tel.: +86-20-84744772

Abstract: The climate in hot-moist regions like Guangdong is characterized as short in summer and long in winter, which imposes high insulation requirements on the roof of houses. In this case, this paper proposes a roof greening overhead structure, which is developed by making a bracket under the existing planting box after reinforcing the bottom thereof, thus there will be an overhead layer with a height of 300mm between the planting box and the roof. The study used three office rooms with identical conditions on the top floor of the office building as the test rooms. The roofs of the three rooms were set as the roof with the overhead planting box, the roof with the existing planting box and the reference roof, respectively. The temperatures of the structural layers in the three test rooms were measured under the non-air-conditioning closed conditions in summer. The hourly power consumptions of the air-conditioners in the three test rooms were measured under the air-conditioning closed conditions in summer. The results indicates the natural ventilation formed by the overhead structural layer can improve the overall insulation effect of the roof. The energy saving rates of the air-conditioners in the room with the overhead planting box on the roof reached 28.2%.

1. Introduction

The serious environmental problem today is quite opposite to the rapid economic development. Large-scale urbanization has worsened the urban environment. For example, the air quality cannot reach the standard, and the heat island effect is prominent. To our delight, roof greening can greatly adjust the urban climate and relieve the heat island effect. The climate in hot-moist regions like Guangdong is characterized as short in summer and long in winter, which imposes high thermal insulation requirements on the roof of houses. The roof greening technology can not only significantly improve the roofing landscape, but also purify the air, quite suitable to be popularized in such regions [1-3]. The most traditional roof greening is laying vegetation on the roof directly, which requires an extremely-high waterproof performance of the roof [4]. As the technology become mature, people begin to use lightweight roof greening boxes that are easy to move and maintain. However, practical applications show that the planting boxes on the roof affect the roof drainage. Therefore, they are prone to cause roof ponding as rainstorms often occur in hot-moist regions. The roof greening plants are usually drought-tolerant and heat-resistant, but excessive waterlogging often results in extensive death of them, thus affecting the popularization of the roof greening technology.

The overhead ventilation roof is widely applied in southern China. Especially in summer when the climate is hot and rainy, this roof structure shows its superiority[5-6]. The cooling principle of the
overhead ventilation roof is that: for one thing, the solar radiation directly irradiated to the roof is shielded by the outer layer of the ventilation interlayer, so that the roof is subject to twice heat transfers; for another, the natural ventilation is formed under the action of wind pressure and hot pressure, so that the solar radiant heat absorbed by the upper and lower surfaces of the visor exposed to the air is transferred to the air and dissipated by the wind. The greater the wind speed is, the more heat will be dissipated[7-8]. This greatly improves the insulation capacity of the roof, thereby reducing the influence of the outdoor heat on the indoor temperature. In view of the climate characteristics of heavy rains and water accumulation in hot-moist regions like Guangdong, this paper proposes a roof greening overhead structure, which is developed by making a bracket under the existing planting box after reinforcing the bottom thereof, thus there will be an overhead layer with a height of 300mm between the planting box and the roof. The structure can protect the greening plants against waterlogging, without affecting the roof drainage. Even more noteworthy is that all the test brackets of this structure survived intactly while the super typhoon "Mangosteen" was passing by in September 2018.

The study used three office rooms with identical conditions on the top floor of the training building as the test rooms. The roofs of the three rooms were set as the reference roof, the roof with the existing planting box and the roof with the overhead planting box, respectively. Through the comparison of the temperature curves of the structural layers of the three test rooms under the non-air-conditioning closed conditions in summer, the cooling effect of the roof greening overhead structure was explored. Besides, the energy saving rate was also calculated by comparing the hourly power consumptions of the air-conditioners in the three test rooms measured under the air-conditioning closed conditions in summer.

2. Test

2.1. Test Site
The test region Guangzhou, is located in the northern part of the Pearl River Delta, with a typical monsoon ocean climate. The period from July to September is the hottest time of a year. The test site was namely the roof of the training building. An automatic meteorological recorder was installed 5m away from the test site, to monitor and record the meteorological data including weather, humidity, wind direction, wind speed and rainfall on the hourly basis every day. The recording was continuous during 24 hours per day, and the data was automatically collected once every 5min and transmitted to the computer through the data cable for data backup. The test was conducted from September 19 to September 30, 2018, and the outdoor ambient temperatures, humidity curves and daily rainfalls recorded during the test are shown in Fig.1.
2.2 Test Design
The study used the top floor of a training building in a university in Guangzhou as the test site. The training building has 5 floors, and its surrounding environment is unobstructed. The test roof was full of sunshine, without shadow. The three continuous office rooms on the top floor were selected as the test rooms. The roof of the first test room was naked, used as the reference roof; the roof of the second test room was covered with the Sedum lineare Thunb planting box, and the roof of the third test room was covered with the overhead Sedum lineare Thunb planting box. The three test rooms were all 7.2 meters long and 3.6 meters wide. There was only one eastward window, without a western exposure as the sun louver was available. In order to reduce the influence of the window on the test results, the window was sealed with insulation board. The test was carried out during the summer vacation, and no person accessed to the test rooms after they were made closed, which reduced the impact of environmental factors on the test results.

2.3 Outdoor and indoor environmental monitoring

![Fig 2. Measuring Points Distribution Diagram](image)

The temperature curves of the structural layers of the three test rooms under the non-air-conditioning closed conditions in summer were recorded by JTNT-A series multi-channel temperature self-recording instrument. One self-recording instrument was set for each of the three rooms. The main unit of the self-recording instrument has a total of 12 temperature channels which could collect data.
independently. A thermocouple probe was used to measure the temperature of each measuring point and recorded them automatically. The step size of the temperature data recording was set to 5 minutes. Three measurement points were set in the same positions on the roof surface and ceiling of the first test room, and the roof surface temperature and ceiling temperature were expressed by $T_d$ and $T_c$, respectively; the roof of the second test room was covered with the Sedum lineare Thunb planting box, and three temperature measurement points in addition to the measurement points on the roof surface and the ceiling were set in the proximity of the top surface of the box, expressed by $T_t$; and the roof of the third test room was covered by the overhead Sedum lineare Thunb planting box, and three temperature measurement points in addition to the measurement points on the roof surface and the ceiling, as well as those in the proximity of the top surface of the box were set, expressed by $T_b$.

The hourly air-conditioner power consumptions of the three test rooms under the air-conditioning closed conditions in summer were recorded by the EX-300 electricity recorder, which was connected to the air conditioners’ line of the test rooms, used to record the real-time power consumption during the operation of the air conditioners. The stored data could be transmitted to the computer via the CF card. The air conditioners in the test rooms were newly installed in 2015, which are Gree KF-72LW/A1-N in model, with input power of 2225W, cooling capacity of 7300W, and energy efficiency ratio of 3.28. The air conditioning temperature was set at 24 °C during the test.

3. Results and Discussion

3.1. Analysis on the Cooling Effect of the Outer Surface
The indoor temperature of the test rooms was mainly affected by the outer surface temperature of the roof [9-11]. The heat on the outer surface of the roof is transmitted into the room through heat radiation and conduction. The decrease of the outer surface temperature is conductive to improve the cooling effect of the entire roof structure. The surface temperatures of the three types of roofs are compared in Fig. 3, which indicates that during the test, the maximum roof temperatures of the three types of roofs showed a decreasing trend. By comparing the typical-day temperature curves, it is found that the roof greening plants could significantly reduce the outer surface temperature of the roof, and the cooling effect was particularly remarkable from 12:00pm to 8:00pm in the afternoon. The cooling effect of the test roof with the overhead planting box was basically similar to that of the roof with the existing planting box, just slightly higher than the latter from 11:00am to 3:00pm. The green vegetation layer could quickly reduce the outer surface temperature of the roof due to the absorption and transpiration of green plants. Therefore, the outer surface temperatures of the two roofs with green vegetation were significantly lower than that of the reference roof.

Fig 3. Comparison of Outdoor Surface Temperature Curves on Typical Days
Table 1. Comparison of (Daily) Maximums, Averages, and Differences

| Roof type                  | typical days | Daily average temperature | reduced | Maximum temperature | reduced |
|---------------------------|--------------|---------------------------|---------|---------------------|---------|
| The reference roof        | 20th         | 37.4                      | 56.6    |                     |         |
|                           | 21st         | 37.2                      | 56.3    |                     |         |
|                           | 22nd         | 38.1                      | 59.9    |                     |         |
| The roof with the existing planting box | 20th         | 30.4                      | 42.8    | 13.8                |         |
|                           | 21st         | 32.5                      | 48.5    | 7.8                 |         |
|                           | 22nd         | 33.0                      | 54.5    | 5.4                 |         |
| The roof with the overhead planting box | 20th         | 30.2                      | 42.9    | 13.7                |         |
|                           | 21st         | 32.0                      | 47.8    | 9.3                 |         |
|                           | 22nd         | 32.9                      | 51.6    | 8.3                 |         |

Table 1 compares the daily average temperatures and maximum temperatures of the three types of roofs on three typical days. From the table, it can be seen that the daily average temperatures and maximum temperatures of the two roofs with green planting boxes were significantly reduced compared to those of the reference roof. By comparing the roof with the existing planting box and the roof with the overhead planting box, we also see that the differences between the daily average temperature and the maximum temperature of the roof with the overhead structure was slightly increased, indicating that the overhead structure ventilation layer took away part of the heat, which contributed to the cooling effect of the roof to some degree. According to the comparison of the meteorological data of one month, it is found that the cooling effect of green planting boxes was very significant within three days after the rain. Thereafter, the transpiration of the plants was weakened due to lack of water, and the temperature difference gradually decreased.

3.2. Comparison of Indoor Cooling Effects

![Figure 4. Comparison of Typical-day Inner Surface Temperature Curves](image)

Table 2. Comparison of (Daily) Maximums, Averages, and Amplitudes

| Roof type                  | The reference roof | The roof with the existing planting box | The roof with the overhead planting box |
|---------------------------|--------------------|----------------------------------------|----------------------------------------|
| Typical days              | 20th               | 21st                                   | 22nd                                   | 20th               | 21st               | 22nd               |

5
Daily average temperature/℃ | 33.3 | 34.1 | 34.5 | 30.7 | 31.2 | 31.5 | 29.8 | 30.4 | 30.9  
reduced/℃           | 2.6  | 2.9  | 3.0  | 3.5  | 3.7  | 3.6  |

The energy-saving thermal performance of roof greening is generally evaluated by the equivalent thermal resistance. Different building envelopes have different temperature wave attenuations to the outdoor surface heat of the outer surface, so the change amplitude in the inner surface temperature is smaller than that of the outdoor temperature, and the change time is later than that of the latter. This characteristic is called thermal inertia [12]. Therefore, the inner surface temperature of the roof greening is an important indicator to evaluate the insulation effect.

Fig 4 compares the typical-day indoor ceiling surface temperatures of the test rooms with different types of roofs. The results were exactly as expected. The ceiling surface temperature of the reference roof was the highest, that of the roof with the existing planting box was secondary, and the roof with the overhead planting box had the lowest ceiling surface temperature. The ceiling surface temperature of the reference roof on the typical days dropped first, then rose back with the increase of the outer surface temperature of the roof after 12:00pm, and reached the temperature peak at approximately 9:00pm, while the corresponding values of two roofs with green planting boxes were very stable. By comparing the daily average temperatures of three typical days, it can be seen that the daily average ceiling surface temperatures of the roof with the overhead planting box and the roof with the existing planting box were reduced by 3.6 °C and 2.8 °C, respectively.

3.3. Analysis on the Cooling Effect of the Overhead Layer

Fig 5. Comparison of Temperature Curves of Upper and Lower surfaces of the Overhead Layer on Typical Days

An analysis was carried out using the typical-day data taken from the test results. Fig.5 shows the comparison of the temperature curves of the roof with the overhead planting box, and the roof without the ceiling surface temperature, relative to the temperature of the original roof. We can see that the cooling effect of the overhead structural layer was mainly reflected in the period from 8:00am to 5:00pm, reducing the temperature by 1~2°C and delaying the occurrence of the temperature peak by about 2 hours compared to the original values, indicating the natural ventilation of the overhead layer could improve the insulation effect of the green planting box.
3.4. Analysis of Energy Saving Effects

![Comparison of Typical-day Hourly Air Conditioner Power Consumption Curves](image)

The hourly power consumptions of the air-conditioners in the three test rooms were tested for 7 consecutive days under air-conditioning closed conditions in summer. By comparing the typical-day hourly power consumption curves as shown in Fig.6, it is found that the power consumptions of the air-conditioners in the rooms with planting boxes on the roof were greatly reduced, and the decrease of the power consumption corresponding to the overhead planting box was more obvious. According to the comparison of the average daily power consumptions of the three rooms, the air-conditioner energy saving rates of the room with the existing planting box on the roof, and the room with the overhead planting box on the roof reached 21.7% and 28.2%, respectively.

| Table 3. Comparison of Average Daily Power Consumption and Energy Saving Rates |
|---------------------------------|-----------------|-----------------|
| Average daily power consumption / kW·h | 15.95 | 12.49 | 11.46 |
| Energy saving rates /% | 21.7 | 28.2 |

4. Conclusions

Roof greening technology not only has remarkable thermal insulation effect, but also beautifies the roof landscape and purifies the air, which is very suitable for promotion in hot and humid areas such as Guangdong. But in practical application, it is found that the roof drainage will be affected by planting boxes placed on the roof. There are many rainstorms in hot and humid areas. Water accumulation is easy to form on the roof. Roof greening vegetation is usually drought-resistant and heat-resistant, but it is easy to die in large areas after waterlogging, which affects the popularization of roof greening technology. This paper puts forward an overhead structure for roof greening. The results are as follows:

1. Outer surface cooling effect: By comparing the typical-day temperature curves, it can be seen that the roof greening plants could significantly reduce the outer surface temperature of the roof, and the cooling effect was particularly remarkable from 12:00pm to 8:00pm in the afternoon.

2. Indoor cooling effect: The average daily temperatures of the roof with the overhead planting box and the roof with the existing planting box were reduced by 3.6 °C and 2.8 °C, respectively, and the temperature curve was relatively flat.

3. Cooling effect of the overhead structural layer: It was reflected in the period from 8:00am to 5:00pm, reducing the roof temperature by 1~2°C and delaying the occurrence of the temperature peak.
by about 2 hours compared to the original values, which indicates the natural ventilation formed by the overhead structural layer can improve the overall insulation effect of the roof.

4. The hourly power consumptions of the air-conditioners in the three test rooms were measured under the air-conditioning closed conditions in summer. By comparing the typical-day hourly power consumption curves, it is found that the energy saving rates of the air conditioners in the room with the existing planting box on the roof and that with the overhead planting box on the roof reached 21.7% and 28.2%, respectively.

Acknowledgments
This work was supported by National Science Foundation of China (Grant NO.51878287), the New Theory and Methodology for Object- & Effect-Oriented Green Building Design (Grant NO. 2016YFC0700200), Science and Technology Program of Guangzhou, China (Grant NO. 201804010488).

References
[1] Liu, Z., Liu, Y., He, B.-J., Xu, W., Jin, G., Zhang, X. (2019) Application and suitability analysis of the key technologies in nearly zero energy buildings in China. Renewable and Sustainable Energy Reviews, 101: 329-345.
[2] Almeida, M., Ferreira, M. (2017) Cost effective energy and carbon emissions optimization in building renovation (Annex 56). Energy and Buildings, 152: 718-738.
[3] Qin, Y., Zhang, M., Hiller, J. E. (2017) Theoretical and experimental studies on the daily accumulative heat gain from cool roofs. Energy, 129: 138-147.
[4] Qin, Y., He, Y., Wu, B., Ma, S., Zhang, X. (2017) Regulating top albedo and bottom emissivity of concrete roof tiles for reducing building heat gains. Energy and Buildings, 156: 218-224.
[5] Han, Y. (2009) A study on energy-saving building roofs. Journal of Hefei University(Natural Sciences Edition), 19: 58-61.
[6] Deng, Z., Zhang, L., Zhang, Y., Ma, L., Meng, Q., Ruan, L., Dai, S., Li, Z. (2018) Heat Transfer Model of Green Roof Based on Dynamic Optical Parameters of Vegetation Canopy. Building Science, 34: 115-120.
[7] Li, X., Tang, J., Lin, D. (2013) Experimental Study of Air Flow Characteristics in the Overhead Ventilation Roof. Building Energy Efficiency, 41: 5-7.
[8] Wang, J., Han, X., Zhang, Y., Zhang, L., Meng, Q. (2018) Measurement of hygric properties of porous paving materials. Journal of Civil, Architectural & Environmental Engineering, 40: 20-26.
[9] Li, L., Zhou, X., Zhao, L., Meng, Q. (2016) Experimental study on rain’s effect on heat transfer of walls in Guangzhou. Heating Ventilating & Air Conditioning, 46: 132-137.
[10] Wang, J., Meng, Q., Zhang, L., Zhang, Y., He, B., Zheng, S., Santamouris, M. (2019) Impacts of the water absorption capability on the evaporative cooling effect of pervious paving materials. Building and Environment, 151: 187-197.
[11] Wang, J., Meng, Q., Tan, K., Zhang, L., Zhang, Y. (2018) Experimental investigation on the influence of evaporative cooling of permeable pavements on outdoor thermal environment. Building and Environment, 140: 184-193.
[12] Liu, H., Zhang, G., Huang, Y., Qu, S., Xie, W. (2016) Energy Efficiency and Temperature Reduction Based on Green Roof. Building Energy Efficiency, 309: 46-51.