RESEARCH

THERMAL PERFORMANCE OF FELT TYPE VEGETATED FACADE SYSTEMS IN A TEMPERATE CLIMATE DURING HEATING AND COOLING PERIODS

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ABSTRACT

Using vegetated facade systems (VFS) as a sustainable solution for existing and new buildings and evaluating thermal performance of these sytems are not a new concept. However, there is a gap in literature about measuring thermal performance of VFS applied on an insulated wall. Also, in the research literature, there are few studies measuring thermal performance of felt type VFS in temperate climates, and data about the thermal performance of VFS during winter periods is still scarce. Thus, the aim of the present study is to measure the thermal performance of a felt type VFS applied on a thermal insulated existing wall that us located in Kocaeli, Turkey, under Csa climate conditions during heating and cooling periods. Test results indicate that the felt type VFS acts as a shading device and has a positive contribution to the thermal performance of building walls during a cooling period. In daytime when there is a high amount of solar radiation, felt type VFS decreased exterior surface temperatures of the insulated existing wall by a maximum of 24.4°C, 32.2°C and 37.2°C, in spring, summer and fall periods, respectively. Additionally, indoor air temperatures of the vegetated facade were lower than indoor air temperatures of the reference facade with the maximum difference of 1.8°C during the cooling period. Also, test results indicate that the vegetated facade never dropped to below 0°C while exterior surface temperatures of the reference facade dropped below 0°C at nighttime in the winter period. Thus, it can be claimed that the felt type VFS behaves as a thermal buffer and enhances the thermal performance of the exterior wall of the existing building during heating periods at nighttime. As a conclusion, although differences between exterior surface temperatures of vegetated and reference walls were high, differences between interior surface temperatures of vegetated and reference walls were not meaningful. That is due to the fact that the existing building exterior wall assembly includes 5 cm thickness thermal insulation material which enhance the thermal performance of the brick wall. Finally, according to solar reflectance results, it can be claimed that vegetated facade systems have a positive effect on reducing urban heat island effect.

KEYWORDS

living walls, felt type vegetation facade systems, sustainability, field measurements, thermal performance, surface temperature

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1. INTRODUCTION

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change indicates that the average temperature on earth has increased by 0.75°C from the beginning of the 20th century until today [1]. Additionally, it is predicted that average air temperature will increase by 1.8–4°C at the end of 21st century [2]. Also, it is predicted that the annual average air temperature in Turkey will rise by 2.5–4°C in following years [3]. Urbanization causes reduction of a huge amount of green areas and replaces them with buildings and surfaces with low albedo value [4,5,6]. These changes cause a significant rise of urban temperature known as the heat island effect, which is responsible for the increase of ambient air temperatures [5,7]. Use of vegetated surfaces and vegetated facade systems plays an important role to reduce the urban heat island effect [4,7,8]. The greenhouse effect plays an important role in the increase of ambient air temperatures. The building sector is responsible for 40% of the CO_2 and other greenhouse gases emissions. With improvements in economic development, energy use in the building sector has increased [9,10]. In order to decrease greenhouse gas emissions, it is essential to use renewable energy sources instead of fossil fuels and/or reduce energy consumption. Energy consumption caused by the building sector can be reduced by several sustainable design strategies. One of them is covering walls with vegetation via vegetated facade systems (VFS). "Greenery" is a common term in literature, however, in the present study, it is preferred to designate the nomenclature of these systems as "vegetated facade systems" because the main components of these system are vegetation and growing media. Literature review reveals that vegetated facades minimize heat gain through the building facade, decrease surface temperature and increase the energy efficiency of buildings [9,11,12,13,14,15,16]. Studies in Köppen subgroup "Csa" (mild with no dry and hot summer climate) indicate that vegetated facade systems reduce the maximum exterior surface temperature of the reference building surface up to 25°C in the cooling period [17,18]. Most of the studies in the Csa climate were conducted during the cooling period. Few studies have measured both cooling and heating performance of this system. To give an example, Coma et al. (2017) measured exterior and interior surface temperatures and interior air temperatures of vegetated and reference walls and indicated that the maximum surface temperature reduction was observed for the south oriented vegetated wall by up to 16.5°C. Also, it is stated that the heating load was decreased 4.2% by using the vegetated facade system [19]. Vox et al. (2018) measured exterior surface temperatures of vegetated and reference walls and reported that the exterior surface temperatures of a south oriented vegetated wall were lower than the exterior surface temperatures of reference wall up to 9°C in daytime during the summer period [20]. Also, it is indicated that the exterior surface temperature of a vegetated wall were higher than respective temperatures of a reference wall up to 3.5°C in nighttime during the winter period. These results indicated that the vegetated facade system acted as a thermal screen during summer days in daytime and during winter days in nighttime. The aim of the present paper is to evaluate the thermal performance of a felt type vegetated facade system in Csa climate conditions during spring, summer and fall periods in 2017, and during the winter period in 2018. Also, by means of the results of the present study, it is aimed to fill the gap in literature regarding data of the thermal performance of VFS applied on an insulated wall and lack of data for all periods of the year. Initially, design of the vegetated facade, instrumental setup and measurement parameters are presented. Subsequently, solar radiation and surface temperature results are given and values of both vegetated and reference facades are comparatively assessed.

2. MATERIALS AND METHODS

Thermal performance monitoring was conducted at a building located at the Gebze Technical University, Gebze, Kocaeli, Turkey. Gebze Technical University is located at 40°48'41"N, 29°21'19"E [21]. Kocaeli is classified as "Csa" (mild with dry and hot summer climate) according to Köppen climate classification. The vegetated facade system and instruments were installed in the first week of September 2016. Trial tests were done during the 5 months after installation of the experimental setup. Monitoring, including whole parameters, were started on 04 February 2017.

2.1 Experimental building

An existing office building located on the Gebze Technical University campus was chosen as the experimental building; two facade surfaces of the building were used as the vegetated and reference facades (Figure 1). Both facades are oriented to the south. They are exposed to solar radiation for the majority of the day (especially hours when solar radiation reaches high values), and there are no obstructions in front of the facades. Also, there is no opening in the respective walls; both facades are fully opaque. Spaces behind both facades are office rooms. These two rooms have approximately similar conditions. Both of them have the same heating and cooling systems, which is an air conditioning system. It operates between 08:00 and 17:00 during weekdays and doesn't operate during weekends. The window to wall ratios of the east

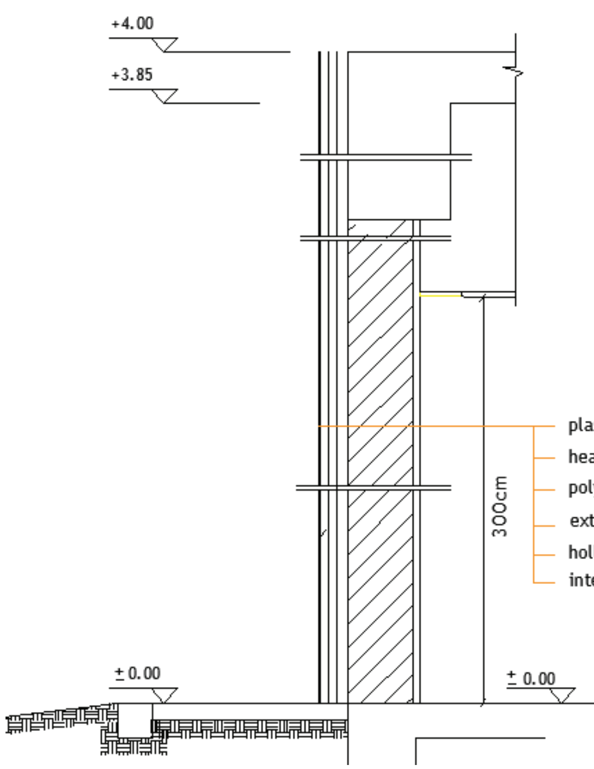
FIGURE 1. General views of the experimental building (left: vegetated wall surface, right: reference wall surface).

side of both rooms are approximately similar (wwr: 20% for vegetated facade, wwr: 13% for reference facade).

The existing wall system of the building is composed of the following components from inside to outside: 19 cm brick wall with 2 cm thickness interior plaster and 5 cm thickness expanded polystyrene heat insulation material and 3 cm thickness exterior plaster. This wall system is considered to be the reference wall system (Figure 2).

The most widely used vegetated facade system in Turkey is a "non-integrated felt system" [22]. Additionally, there is no previous experimental study in which the thermal performance of a "non-integrated felt system" under Csa climate region has been measured during a whole heating and cooling period [23, 24]. Therefore, the "non-integrated felt type" was chosen as the vegetated facade system. Also, "euonymus japonica" was selected due to its successful adaptation to survive in temperate and Mediterranean climates. The vegetated facade is composed of two main components: existing wall system and vegetated system. The vegetated system consists of the following components from inside to outside: galvanized steel frame (40x40x2 mm vertical and horizontal box profiles) mounted on the wall, PVC panel of 1 cm thickness fixed on this frame, first and second layers of geotextile felt (1000gr/m^2) attached on it, and vegetation layer "eounymus japonica" embedded the felt pockets (Figure 3). There is also an open air gap with 15 cm thickness between the exterior wall and the PVC panel. The other components of the VFS are drainage and irrigation elements. There are two drip irrigation pipes which are 4.5 meters in length and 25 mm in diameter that is mounted on the first felt layer. Each pipe has 100 nozzles at 9 cm intervals, and a total of 33 liters of water and fertilizer can be supplied to the system in one hour through these pipes. Irrigation periods are arranged to automatically by

FIGURE 2. Section of the existing/reference wall system assembly.



means of a timer in the summer period to start at 8 am and end at 8 pm and last for 8 minutes per hour. In the winter period, they run from 9 am to 5 pm and last for 5 minutes per hour. Excess water is collected in a drainage channel and discharged into the garden near the building through drainage pipes. Images of all components of VFS are presented in Figures 4 and 5.

FIGURE 3. Section of vegetated facade system assembly.

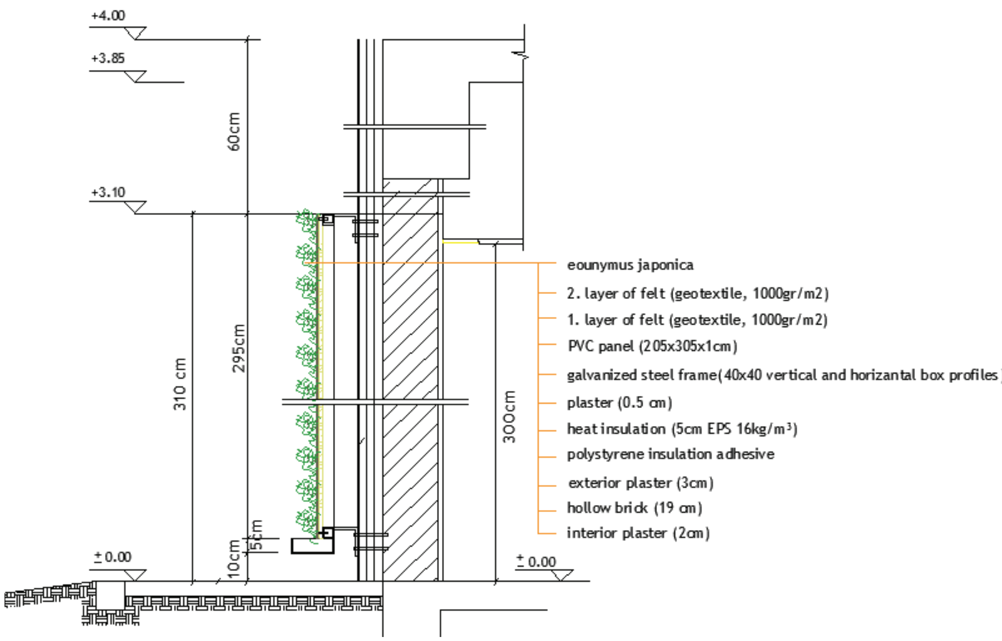


FIGURE 4. Components of VFS: (a) Geotextile felt material, (b) plant "eounymus japonica," (c) drainage channel, (d) drainage pipes, (e) irrigation pipes, (f) fertilizer tank and timer.

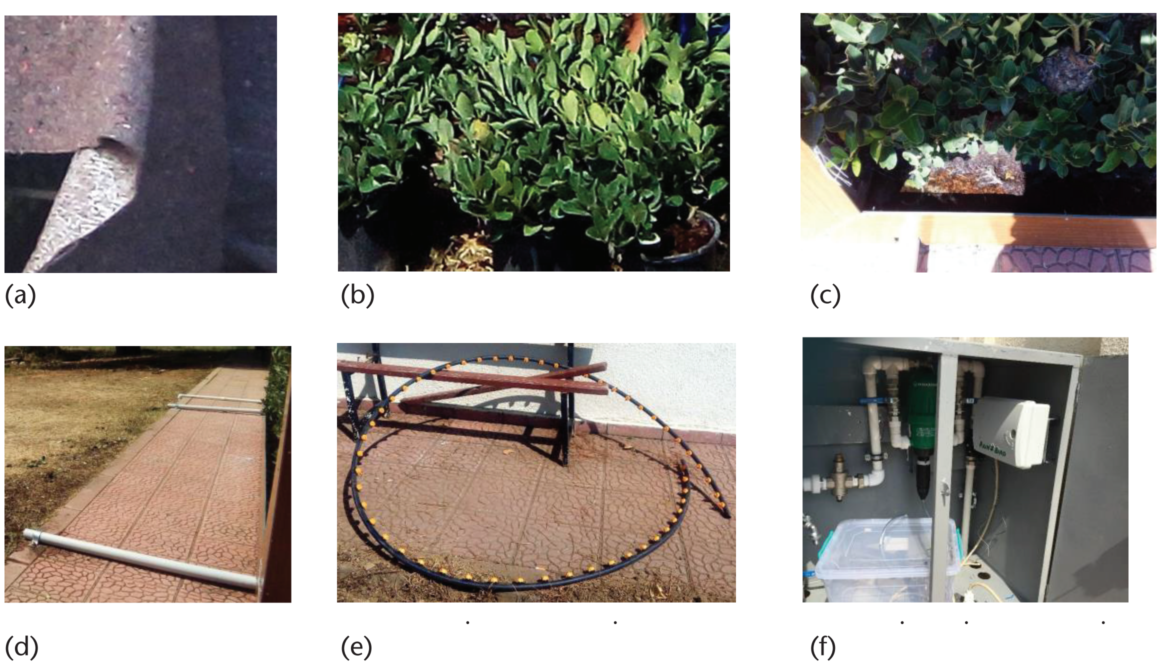


FIGURE 5. Geotextile felt material attached on PVC panel and irrigation pipes mounted on the felt layer (image of VFS before plant layer applied).

2.2 Instrumental setup for monitoring

An instrumental setup was designed and installed at the reference and vegetated facade systems to measure solar reflectance, surface temperature, temperature profile across the wall assembly and climatic data. Figure 6 shows the site plan of the building and location of the meteorological station, reference facade and vegetated facade. Figure 7a demonstrates the scheme of the meteorological station and Figure 7b shows the image of the meteorological station. Figure 8a designates the section of reference facade test assembly and Figure 8b shows the image of the reference facade system. Also, Figure 9a demonstrates a section of vegetated facade test assembly and Figure 9b shows an image of vegetated facade system. The measured parameters, types and position of sensors are described in Table 1. Local meteorological data (air temperature and humidity, atmospheric pressure, wind direction and wind velocity) were measured by a weather station installed on the roof parapet of an existing building (Fig 7, Table 1).

FIGURE 6. Site plan (partial) shows location of meteorological station, reference and vegetated facade.

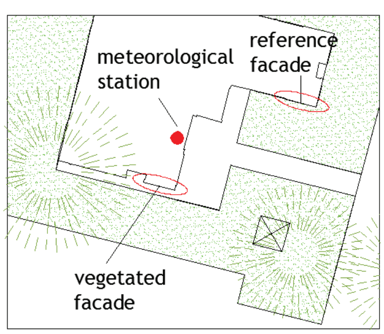
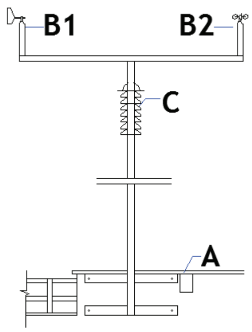


FIGURE 7A,B. Elevation of the meteorological station shows the location of sensors measuring different microclimate parameters (left) and image of the meteorological station on the roof parapet (right).

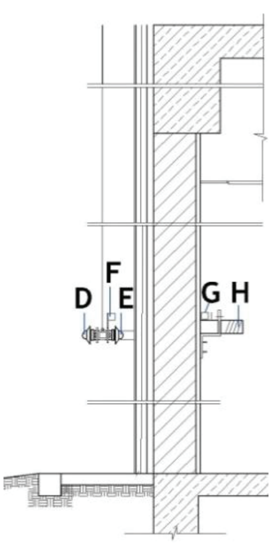


a

b

Three pyranometers were used to measure solar radiation incident and solar reflectance. A pyranometer ("I" in Fig. 9, Table 1) was installed vertically in front of the vegetated facade to measure solar irradiance reflected from the vegetated facade. Two pyranometers were installed in front of the reference facade vertically and mounted back-to-back symmetrically. One of these pyranometers, ("D" in Figure 8a, Table 1) was used to measure solar radiation incident on reference and vegetated facades and the other ("E" in Figure 8, Table 1) measures solar irradiance reflected from the reference facade. Only one pyranometer was decided on to measure incident solar radiation since solar radiation values reaching each of the facades are accepted as identical. Infrared non-contact thermometers were used to measure surface temperatures of the exterior wall of the reference facade ("F" in Figure 8a, Table 1), exterior wall of the vegetated facade ("N" in Figure 9a Table 1), back ("M" in Figure 9a, Table 1) and front ("L" in Figure 9a, Table 1) side of the PVC panel, second layer of felt ("K" in Figure 9a, Table 1). Contact thermometers were used to measure surface temperatures of the interior walls of reference ("G" in Figure

FIGURE 8A, B. Section (left) and image (right) of reference facade test assembly.



a

b

8a, Table 1) and vegetated ("O" in Figure 9a, Table 1) facades. Also, indoor temperature and humidity sensors were placed 20 cm in front of the interior wall surface of the reference ("H" in Figure 8a, Table 1) and vegetated ("P" in Figure 9a, Table 1) facades in order to measure indoor air temperature of the rooms behind the vegetated and reference walls. Additionally, a temperature sensor ("J" in Figure 9a, Table 1) was placed inside the leaves to measure the air temperature among leaves [24]. Location of the sensors are decided according to ISO 10211-1:1995 Standard [33]. All the air and surface temperature sensors and pyranometers are placed about 175 and 180 cm away from ground level and columns in order to avoid thermal bridging caused by any material difference. Surface temperature sensors and pyranometers regarding VFS and RFS can be seen in Figure 10.

FIGURE 9A, B. Section of vegetated facade test assembly(left) and image of vegetated facade system (right).

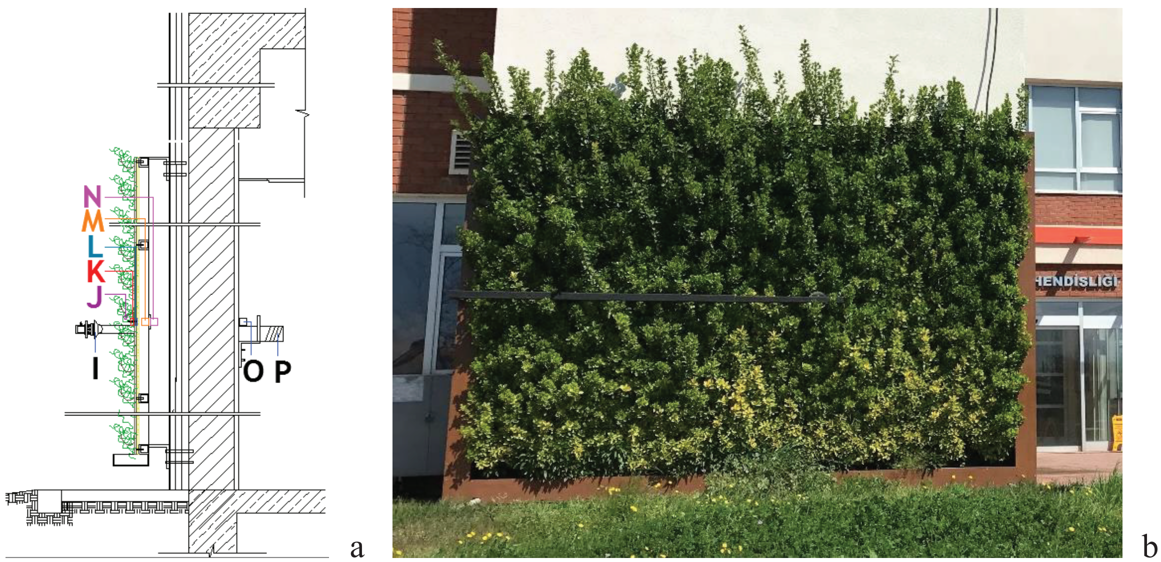


FIGURE 10. Images and location of the sensors: (a) pyranometer in front of VFS, (b) infrared sensors measuring exterior surface temperature of vegetated wall and back side of PVC panel, (c) infrared sensor measuring surface temperature of geotextile felt, and (d) pyranometers in front of RFS

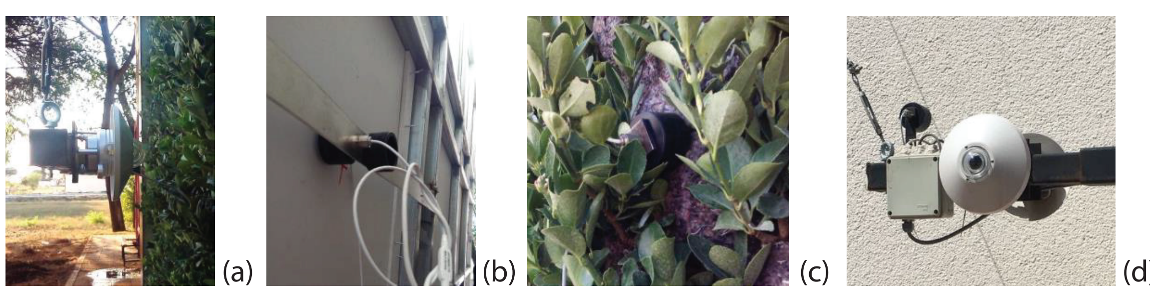


TABLE 1. MEASURED PARAMETERS, TYPE AND LOCATION OF SENSORS [25,26,27,28,29,30,31,32].

Name	Parameter	Unit	Type of sensor	Accuracy	Mounting Position
A Fig.5a	atmospheric pressure	mbar	Comet (T2114) barometric pressure transmitter	±1.3hPa+0.06%	on the roofing parapet of existing building
B1 Fig.5a	wind direction	°	Lambrecht (14576) wind direction sensor	±5°	on the roofing parapet of existing building
B2 Fig.5a	wind velocity	m/s	Lambrecht (14577) wind speed sensor	±2% FS	on the roofing parapet of existing building
C Fig.5a	ambient air temperature and relative humidity	°C %	Comet (T3113D) temperature and humidity transmitter	±0.4°C	on the roofing parapet of existing building
D Fig.6a	solar irradiance reaches to the vegetated and reference facade	W/m^2	Delta Ohm (LP PYRA 02) pyranometer	10 μV/(W/m2)	180 cm above the ground level
E Fig.6a	solar irradiance reflected from reference facade	W/m^2	Delta Ohm (LP PYRA 02) pyranometer	10 μV/(W/m^2)	180 cm above the ground level
F Fig.6a	exterior surface temperature of ref. facade	°C	Optris, CS micro (2WLT15) non-contact thermometer	±1.0°C or ±1.0%	175 cm above the ground level
G Fig.6a	interior surface temperature of ref. facade	°C	Pt 1000/3850 contact thermometer	± (0.3 + 0.005|t|) in °C	175 cm above the ground level
H Fig.6a	indoor air temp. and humidity back of ref. facade	°C	GE HumiTrac temperature and humidity sensor	±0.3°C ±2% or ±5%	175 cm above the ground level
I Fig.7a	solar irradiance reflected from veg. facade	W/m^2	Delta Ohm (LP PYRA 02) pyranometer	10 μV/(W/m2)	180 cm above the ground level
J Fig.7a	air temperature among leaves	°C	Pt 1000 thermometer	—	inside the leaves, 180 cm above the ground level
K Fig.7a	surface temp. of 2.layer of felt	°C	Optris, CS micro (2WLT15) non-contact thermometer	±1.0°C or ±1.0%	175 cm above the ground level
L Fig.7a	surface temperature of front side of PVC panel	°C	Optris, CS micro (2WLT15) non-contact thermometer	±1.0°C or ±1.0%	175 cm above the ground level
M Fig.7a	surface temperature of back side of PVC panel	°C	Optris, CS micro (2WLT15) non-contact thermometer	±1.0°C or ±1.0%	175 cm above the ground level
N Fig.7a	exterior surface temperature of veg. facade	°C	Optris, CS micro (2WLT15) non-contact thermometer	±1.0°C or ±1.0%	175 cm above the ground level
O Fig.7a	interior surface temperature of veg. facade	°C	Pt 1000/3850 contact thermometer	± (0.3 + 0.005|t|) in °C	175 cm above the ground level
P Fig.7a	indoor air temperature and humidity back of veg. facade	°C	GE HumiTrac temperature and humidity sensor	±0.3°C ±2% or ±5%	175 cm above the ground level

3. TEST RESULTS

Monitoring periods included months during 2017 representing spring, summer and fall seasons and winter season 2018. Data regarding each parameter was recorded every 10 minutes during these periods. Nevertheless, user behaviors were found to be different in office rooms during weekdays behind vegetated and reference rooms. Hence, representative weekend days were selected for the spring, summer, autumn and winter periods when high solar radiation was observed and exterior surface temperatures of the reference facade reached maximum values. Also, hours when the exterior surface temperature of the reference wall reached its maximum values during these representative days were selected. Instant values of each parameter on the specified hours were given and cross sections of reference and vegetated facades were drawn. Exterior and interior surface temperatures and indoor air temperatures of vegetated and reference facades obtained on the specified hours of the representative weekend days were compared with each other. Indoor air temperatures were evaluated according to a comfort temperature range identified in ISO 7730 and ASHRAE 55 Standards. Also, the solar reflectance ratio of reference facade and vegetated facades were compared with each other. Solar reflectance ratios were calculated according to ASTM E 1918:2006 [34]. For each representative day and for both facades, the ratio of reflected solar irradiance values to total solar irradiance values was calculated between 10:00–14:00 in winter and 09:00–15:00 in summer. Thus, solar reflectance values for vegetated and reference facades were indicated for each period.

3.1 Results for spring period

April 30, 2017, was chosen as a representative day for the spring period since high solar radiation values occurred and exterior surface temperatures of the reference facade reached maximum values on that day. Ambient air temperature and relative humidity values varied between 12.1°C and 28.3°C, 26% and 84% respectively (Figure 11). The maximum solar radiation reaching the vegetated and reference facade on April 30, 2017, was 466W/m^2 at 14:00. The maximum solar radiation reflecting on the vegetated and reference facade was 125W/m^2 and 367W/m^2, respectively (Figure 12). Solar reflectance of the vegetated and reference facade between 09:00–15:00 were calculated. Solar reflectance values of the vegetated facade and reference facade were 0.32 and 0.86, respectively. Also, the exterior surface temperature of the reference wall reached 50.8°C at 15:10 (Figure 13), and exterior surface temperature of the vegetated wall reached 24.6°C at 15:40 (Figure 14). Reference and vegetated facade temperature cross sections at the time when the exterior surface temperature of the reference facade reached its maximum value is shown in Figure 15. In addition, reference and vegetated facade temperature cross sections at the time when the exterior surface temperature of the vegetated facade reached its maximum value is shown in Figure 16.

3.2 Results for summer period

August 12, 2017, was chosen as a representative day for the summer period because of the high solar radiation values that occurred and exterior surface temperatures of the reference facade reached maximum values reached on that day. Ambient air temperature and relative humidity values varied between 22.4°C and 33.1°C, 29% and 93% respectively (Figure 17). The maximum solar radiation reaching the vegetated and reference facade on August 12, 2017, was 454W/m^2 at 14:10. The maximum solar radiation reflecting vegetated and reference facade was 54W/m^2 and 364W/m^2, respectively (Figure 18). Solar reflectance of vegetated and reference facade between 09:00–15:00 were calculated; solar reflectance values of the vegetated facade and

FIGURE 11. Ambient air temperatures and relative humidity values on April 30, 2017.

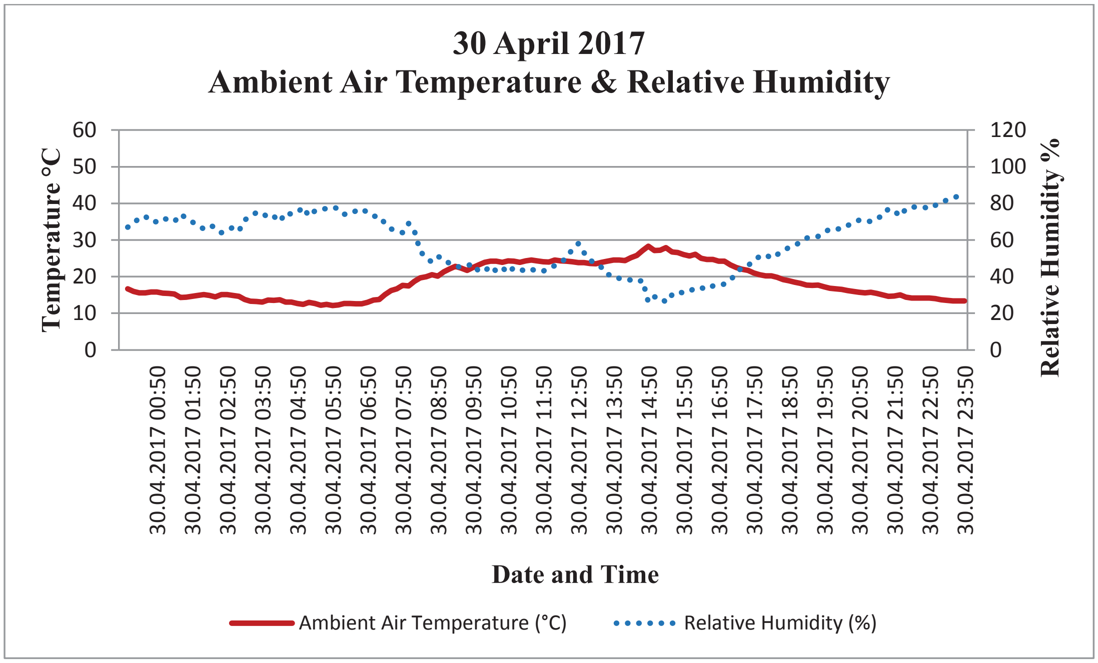


FIGURE 12. Incident and reflected solar radiation values on April 30, 2017.

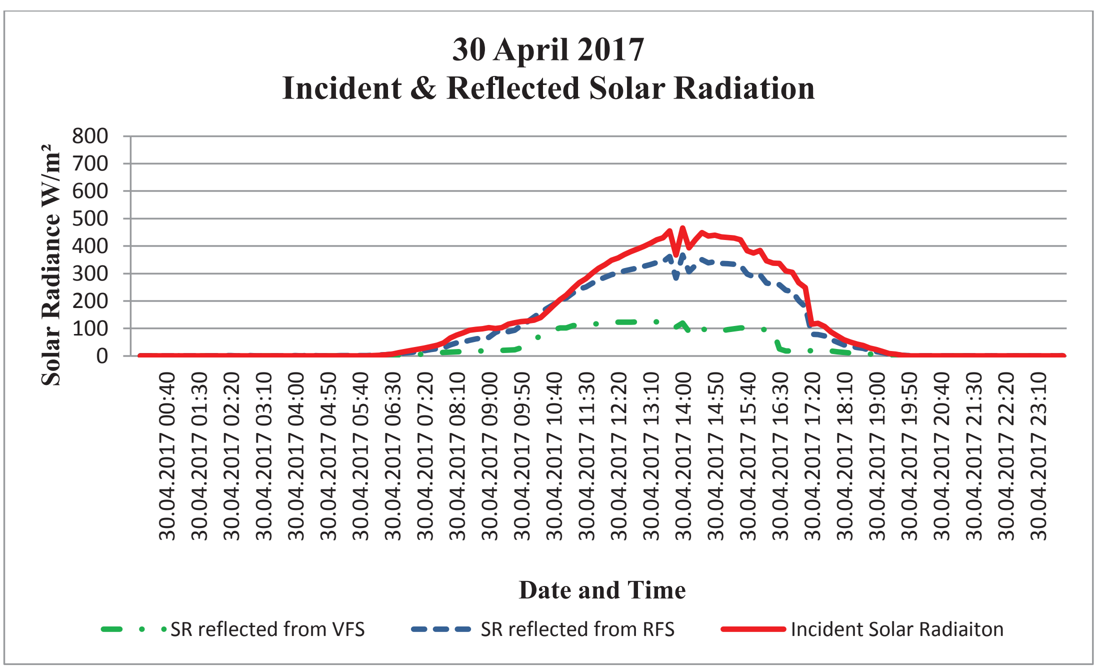


FIGURE 13. Temperature profile of reference facade system on April 30, 2017.

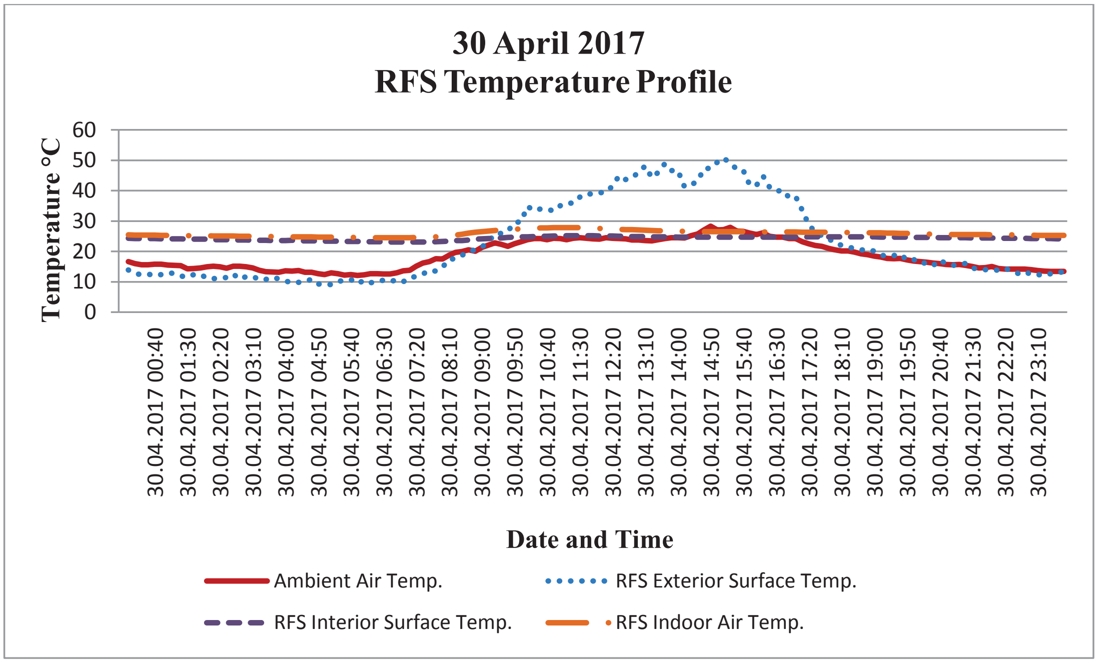


FIGURE 14. Temperature profile of vegetated facade system on April 30, 2017.

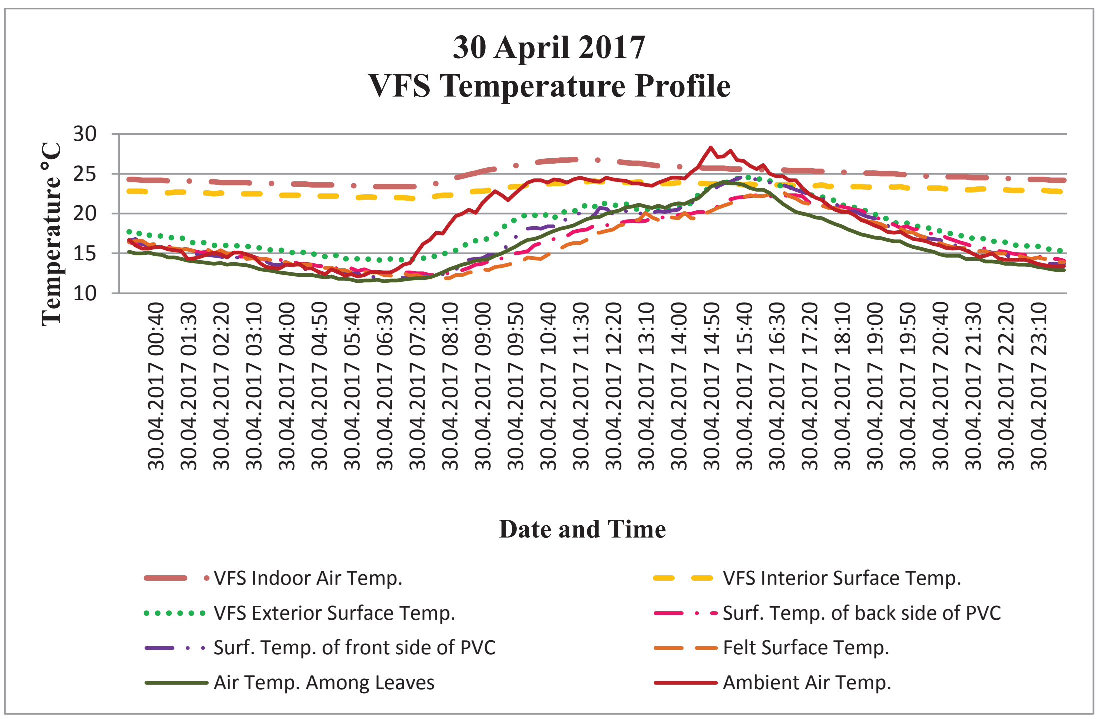


FIGURE 15. Cross sections of reference facade (left) and vegetated facade (right) at 15:10 on April 30, 2017.

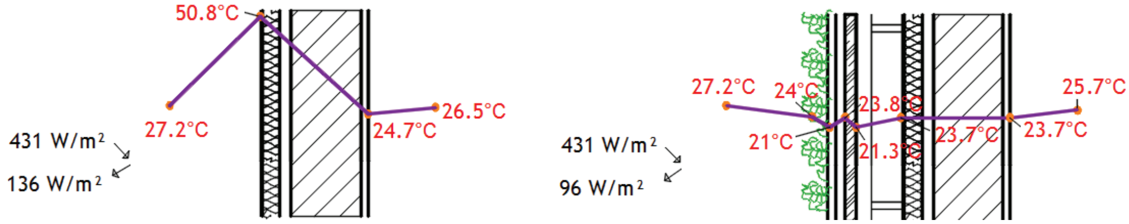


FIGURE 16. Cross sections of reference facade (left) and vegetated facade (right) at 15:40 on April 30, 2017.

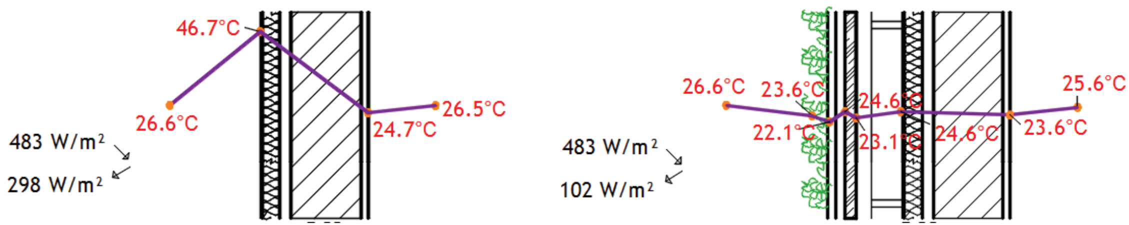
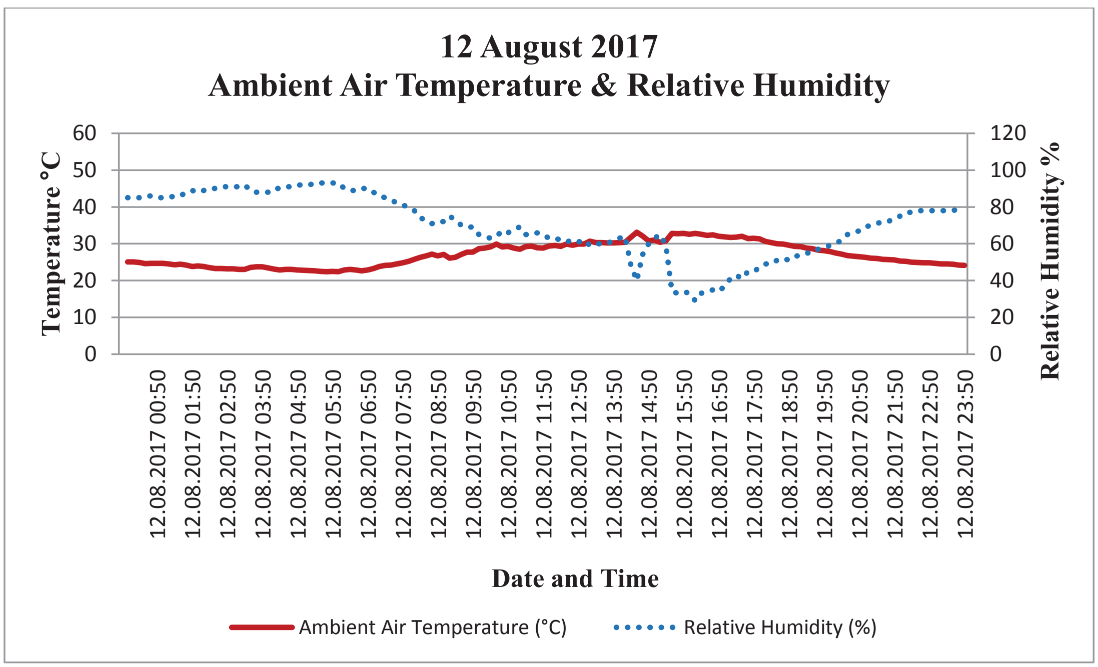


FIGURE 17. Ambient air temperatures and relative humidity values on August 12, 2017.



reference facade were 0.12 and 0.88, respectively. Also, the exterior surface temperature of the reference wall reached up to 53.2°C at 14:40 (Figure 19), and the exterior surface temperature of the vegetated wall reached up to 30°C at 16:40 (Figure 20). Reference and vegetated facade temperature cross sections at the time when the exterior surface temperature of the reference facade reached its maximum value is shown in Figure 21. In addition, reference and vegetated facade temperature cross sections at the time when the exterior surface temperature of the vegetated facade reached its maximum value is shown in Figure 22.

FIGURE 18. Incident and reflected solar radiation values on August 12, 2017.

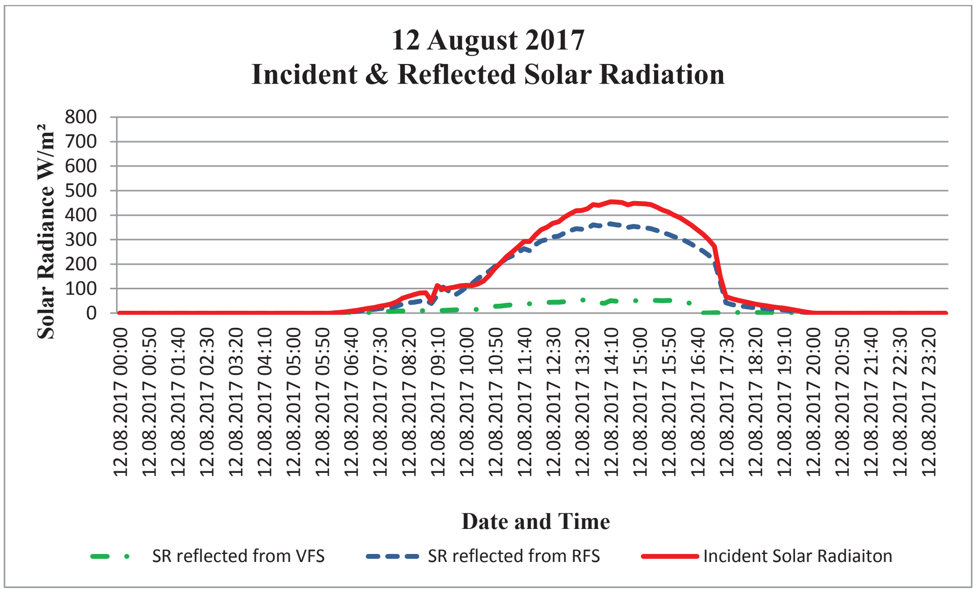


FIGURE 19. Temperature profile of reference facade system on August 12, 2017.

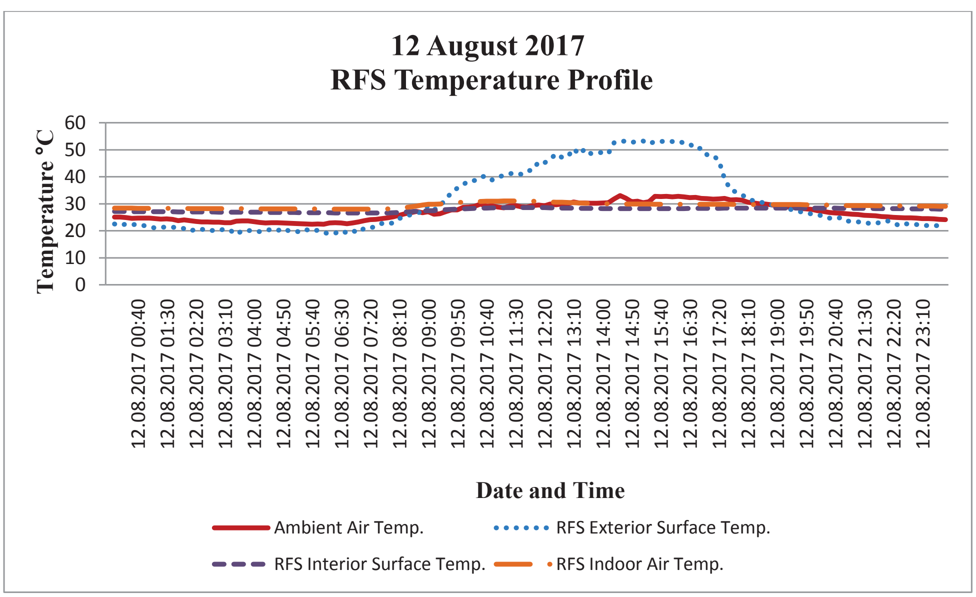


FIGURE 20. Temperature profile of vegetated facade system on August 12, 2017.

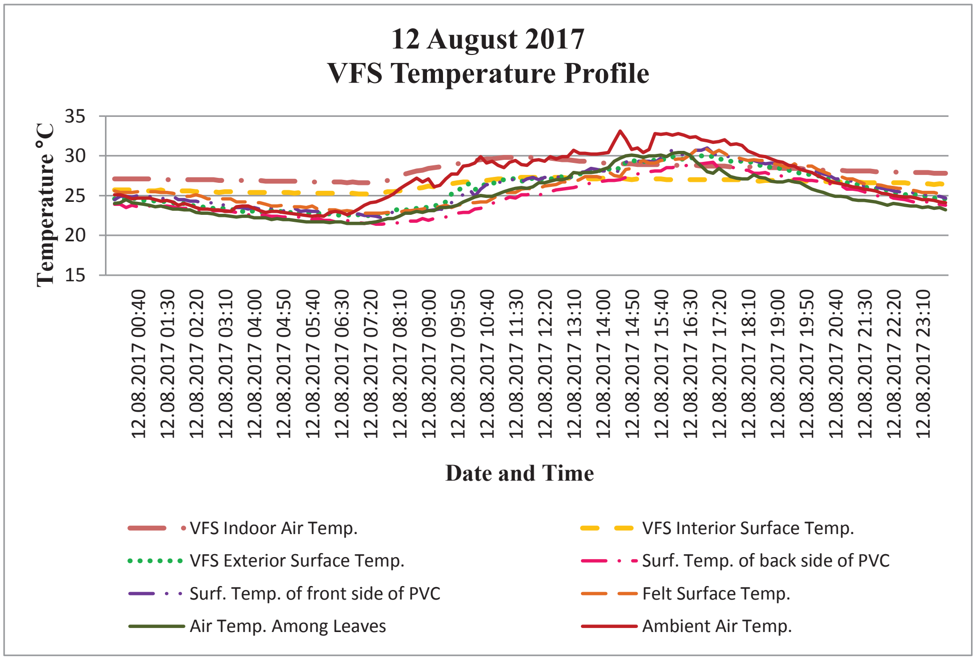


FIGURE 21. Cross sections of reference facade (left) and vegetated facade (right) at 14:40 on August 12, 2017.

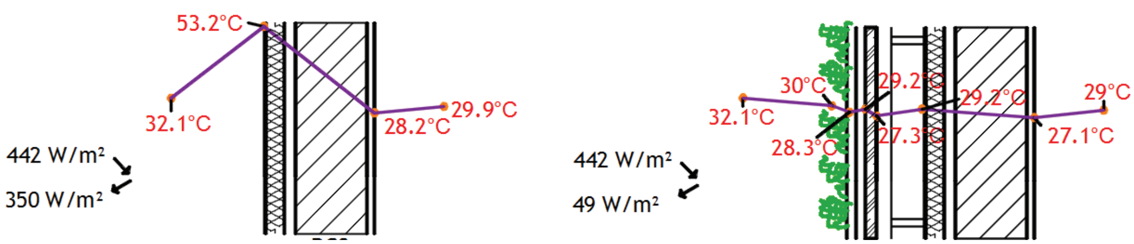
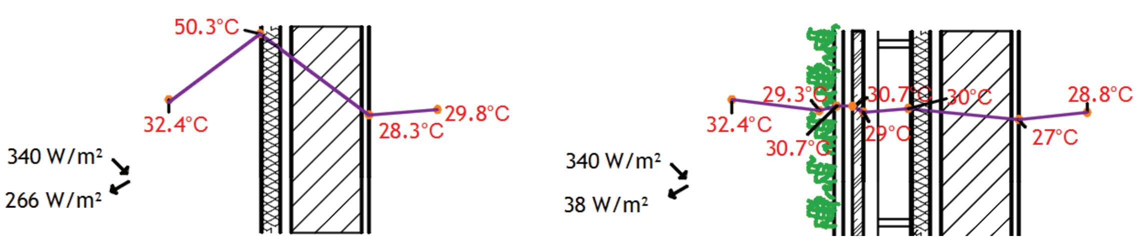


FIGURE 22. Cross sections of reference facade (left) and vegetated facade (right) at 16:40 on August 12, 2017.



3.3 Results for fall period

September 24, 2017, was chosen as a representative day for the fall period due to the high solar radiation values that occurred and the exterior surface temperatures of the reference facade reached maximum values in that day. Ambient air temperature and relative humidity values varied between 13.1°C and 25.6°C, 39% and 93% respectively (Figure 23). The maximum solar radiation reaching the vegetated and reference facade on September 24, 2017, was 642W/m^2 at 14:10; maximum solar radiation reflecting vegetated and reference facade was 73W/m^2 and 448W/m^2, respectively (Figure 24). Solar reflectance of the vegetated and reference facade between 09:00–15:00 were calculated. Solar reflectance values of the vegetated facade and the reference facade were 0.10 and 0.80, respectively. Also, the exterior surface temperature of the reference wall reached 53.3°C at 15:00 (Figure 25), and the exterior surface temperature of the vegetated wall reached 23.6°C at 15:50 (Figure 26). Reference and vegetated facade temperature cross sections at the time when the exterior surface temperature of the reference facade reached its maximum value is shown in Figure 27. In addition, reference and vegetated facade temperature cross sections at the time when the exterior surface temperature of the vegetated facade reached its maximum value is shown in Figure 28.

3.4 Results for winter period

January 07, 2018, was chosen as a representative day for the fall period due to the high solar radiation values that occurred and exterior surface temperatures of the reference facade that reached maximum values on that day. Ambient air temperature and relative humidity values varied between 4.8°C and 16.9°C, 44% and 94% respectively (Figure 29). The maximum solar radiation reaching vegetated and reference facade on January 07, 2018, was 774W/m^2 at 14:50. The maximum solar radiation reflecting vegetated and reference facade was 79W/m^2 and 423W/m^2, respectively (Figure 30). Solar reflectance of the vegetated and reference facades between

FIGURE 23. Ambient air temperatures and relative humidity values on September 24, 2017.

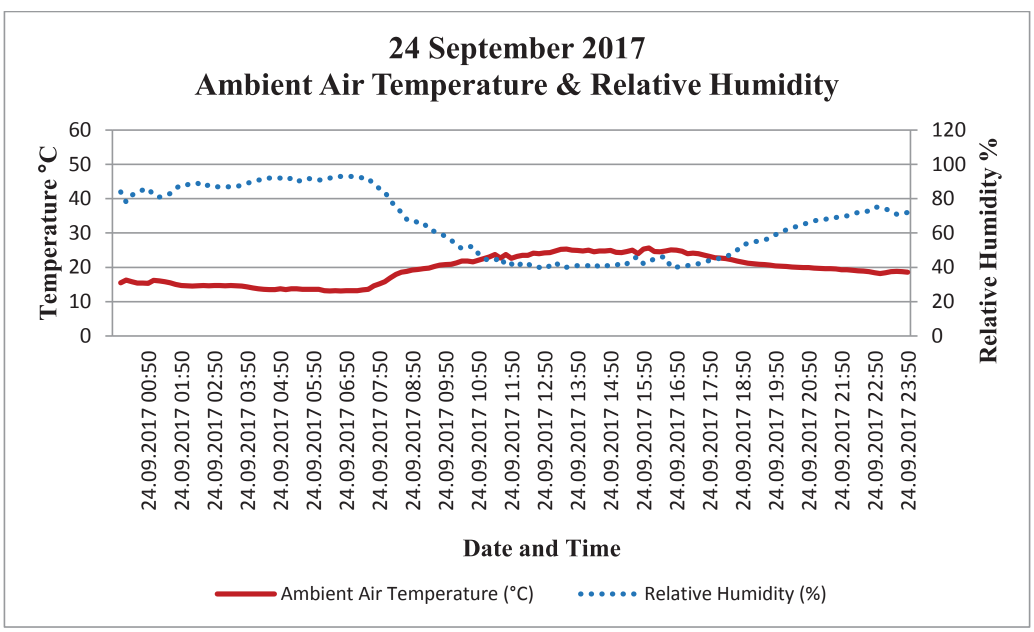


FIGURE 24. Incident and reflected solar radiation values on September 24, 2017.

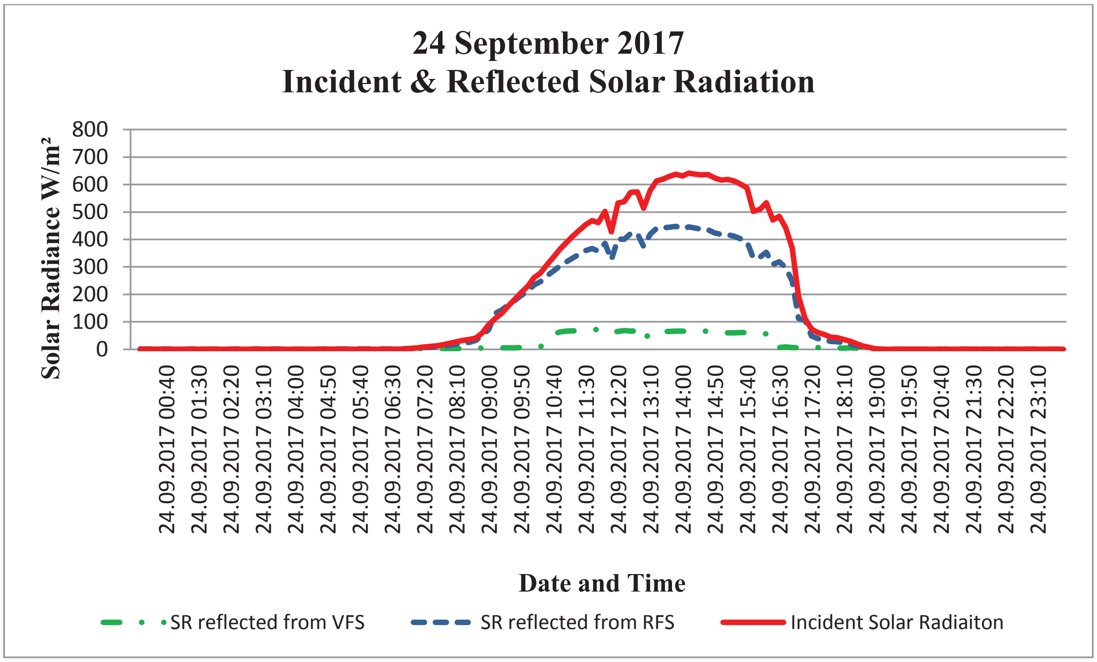


FIGURE 25. Temperature profile of reference facade system on September 24, 2017.

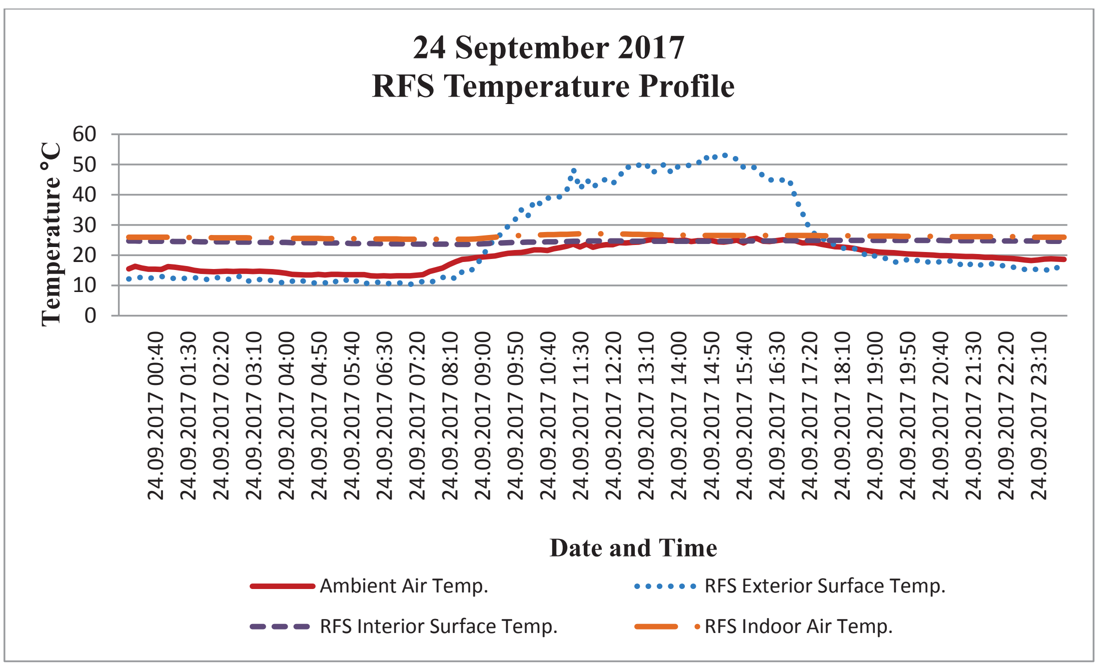


FIGURE 26. Temperature profile of vegetated facade system on September 24, 2017.

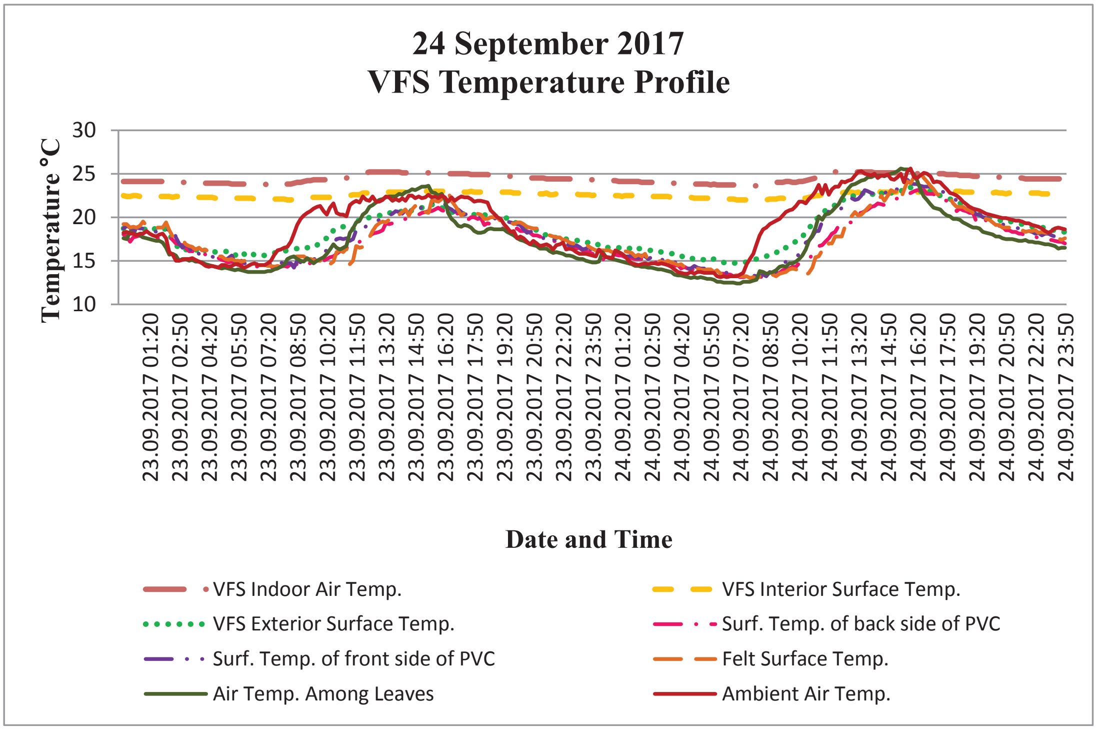


FIGURE 27. Cross sections of reference facade (left) and vegetated facade (right) at 15:00 on September 24, 2017.

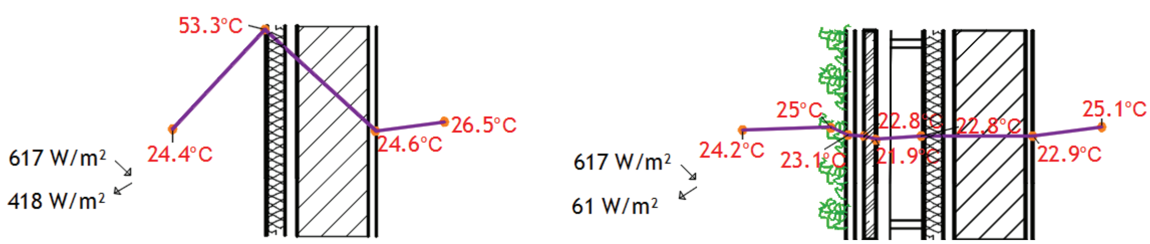


FIGURE 28. Cross sections of reference facade (left) and vegetated facade (right) at 15:50 on September 24, 2017.

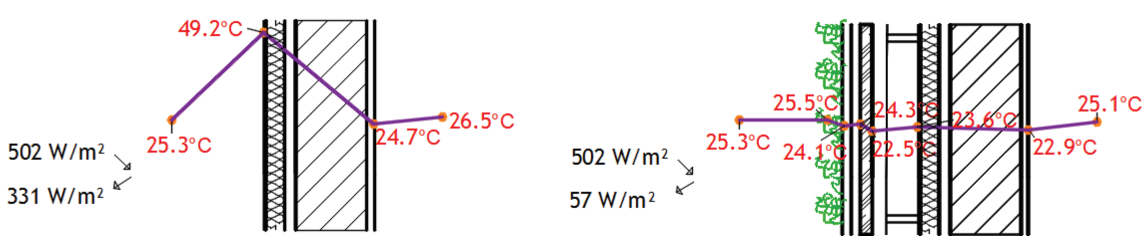


FIGURE 29. Ambient air temperatures and relative humidity values on January 07, 2018.

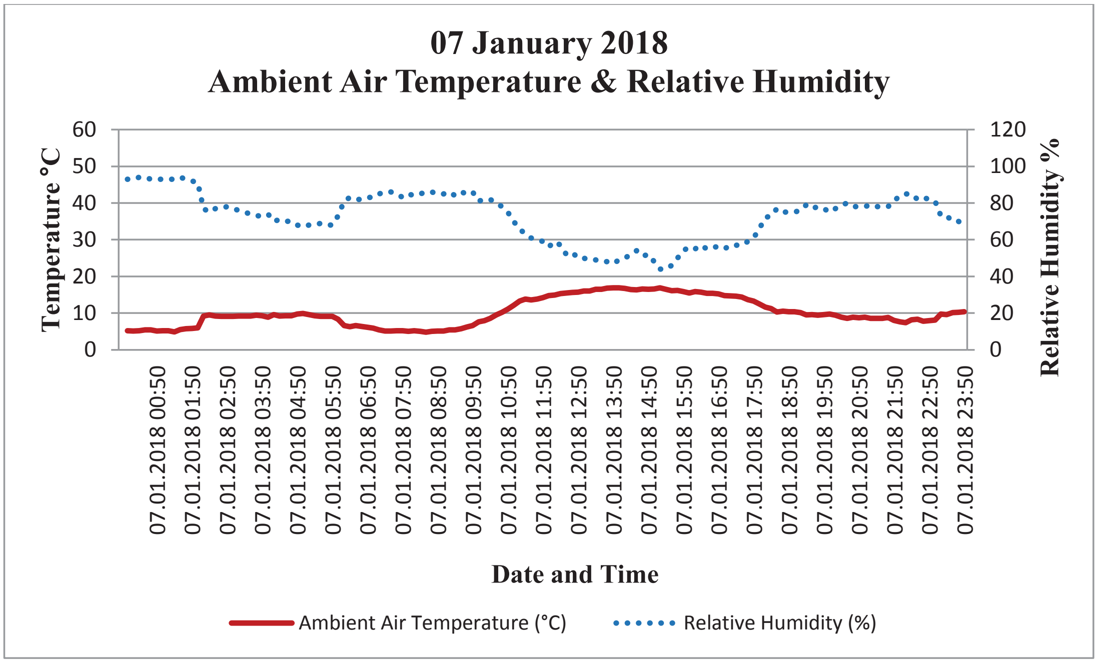
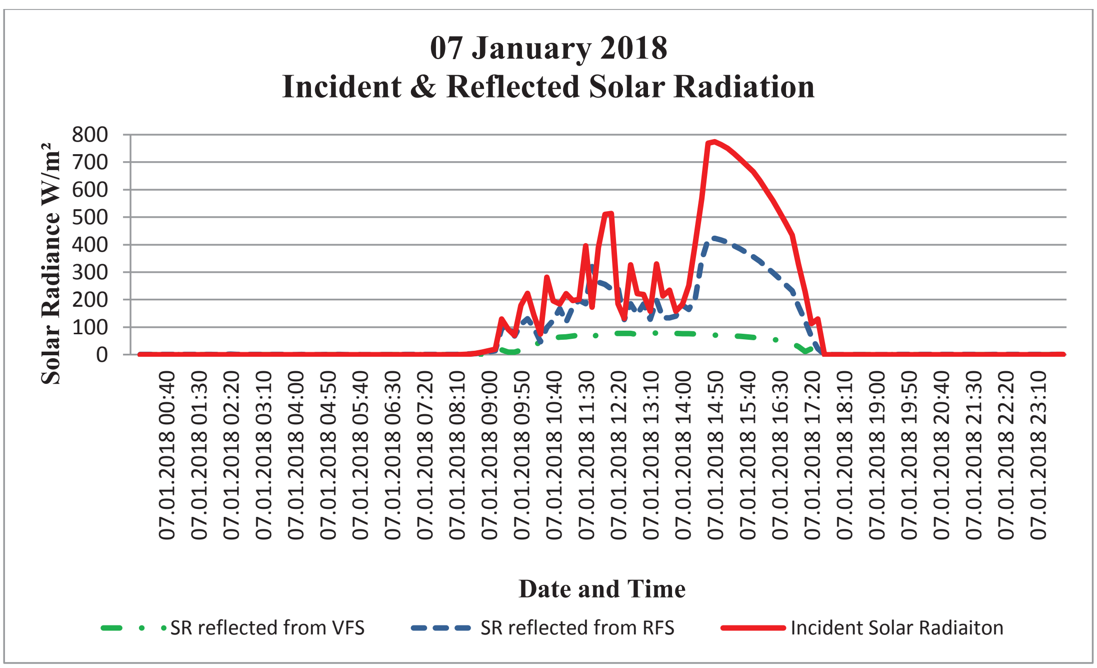


FIGURE 30. Incident and reflected solar radiation values on January 07, 2018.



10:00–14:00 were calculated. Solar reflectance values of the vegetated facade and reference facade were 0.32 and 0.76, respectively. Also, the exterior surface temperature of the reference wall reached 52.6°C at 15:00 (Figure 31), and the exterior surface temperature of the vegetated wall reached 16.2°C at 16:00 (Figure 32). Reference and vegetated facade temperature cross sections at the time when the exterior surface temperature of the reference facade reached its

FIGURE 31. Temperature profile of reference facade system on January 07, 2018.

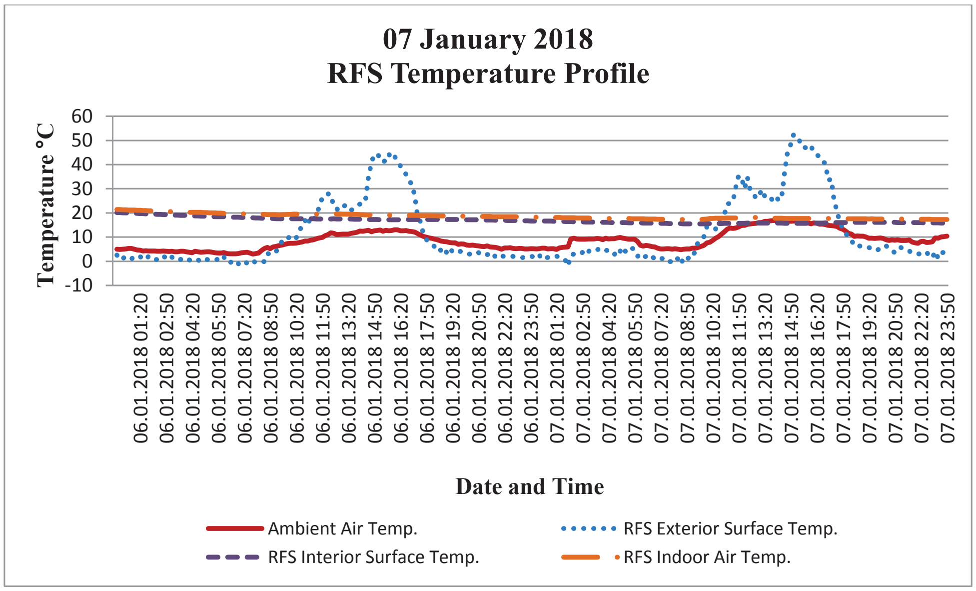


FIGURE 32. Temperature profile of vegetated facade system on January 07, 2018.

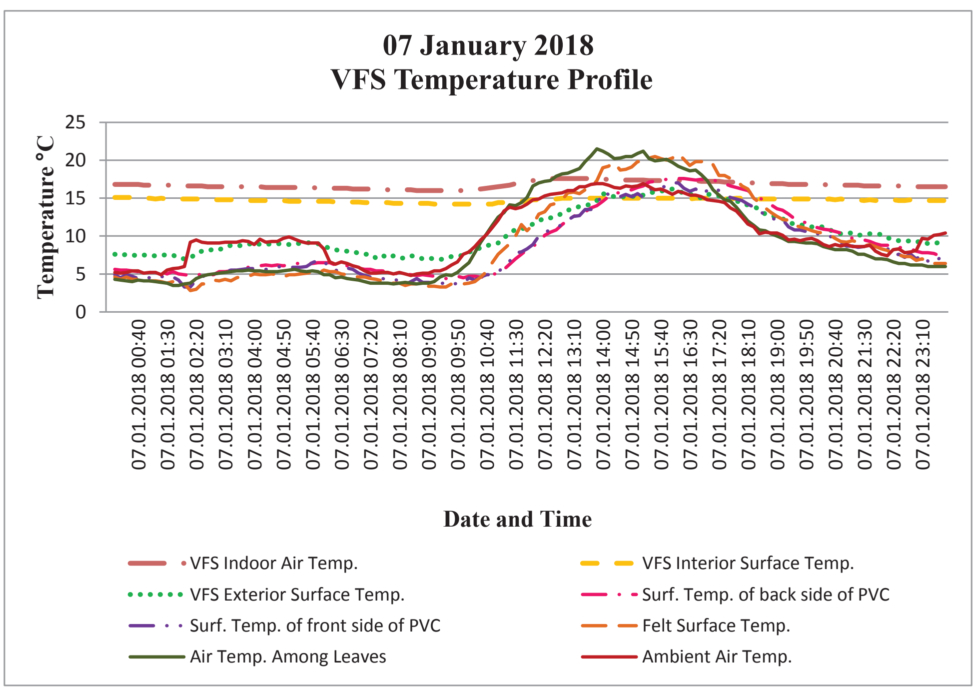


FIGURE 33. Cross sections of reference facade (left) and vegetated facade (right) at 15:00 on January 07, 2018.

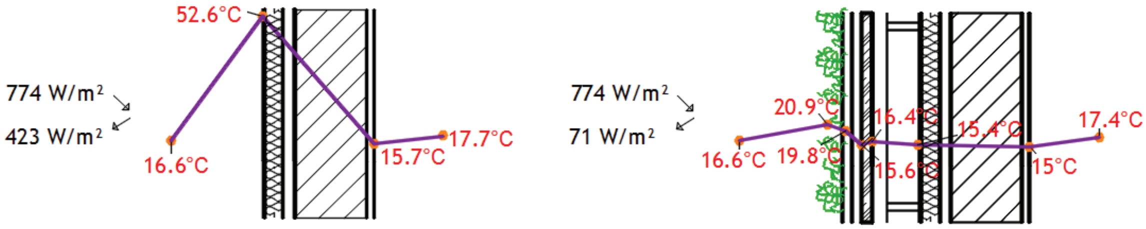
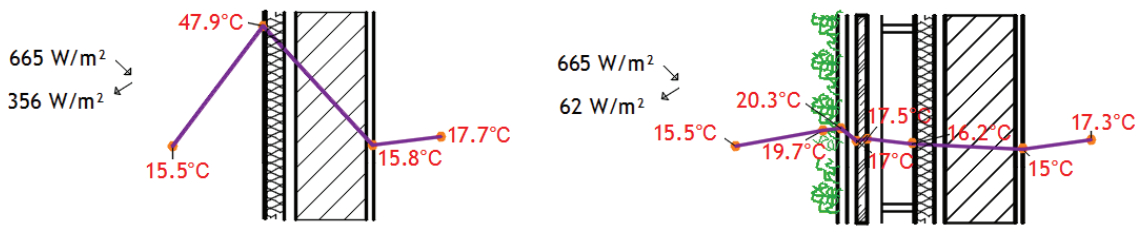


FIGURE 34. Cross sections of reference facade (left) and vegetated facade (right) at 16:00 on January 07, 2018.



maximum value is shown in Figure 33. In addition, reference and vegetated facade temperature cross sections at the time when the exterior surface temperature of the vegetated facade reached its maximum value is shown in Figure 34.

4. RESULTS AND DISCUSSION

The exterior surface temperatures of a vegetated wall were extremely lower than the exterior surface temperatures of a reference wall for each period during the daytime. Differences between maximum exterior surface temperatures of the reference and vegetated facades were 27.1°C, 24°C, 30.5°C and 37.2°C for representative days of spring, summer, fall and winter periods, respectively. Whereas this result is positive for a cooling period, it is not favorable for a heating period. Also, during the nighttime, exterior surface temperatures of the vegetated wall were higher than the exterior surface temperatures of reference walls for each period (Figures 35–38). In addition, the exterior surface temperatures of the vegetated facade never dropped below 0°C, while exterior surface temperatures of the reference facade dropped below 0°C at nighttime during the winter period (Figure 38). These results indicate a positive contribution of VFS to enhance the thermal performance of the exterior walsl of the existing building during the heating period in nighttime. The results from the winter period showed similarities with the results indicated by Vox et al., 2018. Vox et al. (2018) revealed that thermal screen behavior of VFS is desirable in nighttime during the winter period to decrease heating energy loads. Interior surface temperatures of the reference facade were also higher than interior surface temperatures of the vegetated facade duirng the daytime. However, differences between interior surface temperatures of the reference and vegetated facades are negligible (Figures 35–38). Figures regarding the cross section of both facades show that differences between maximum

FIGURE 35. Exterior and interior surface temperatures of reference and vegetated facades on April 30, 2017.

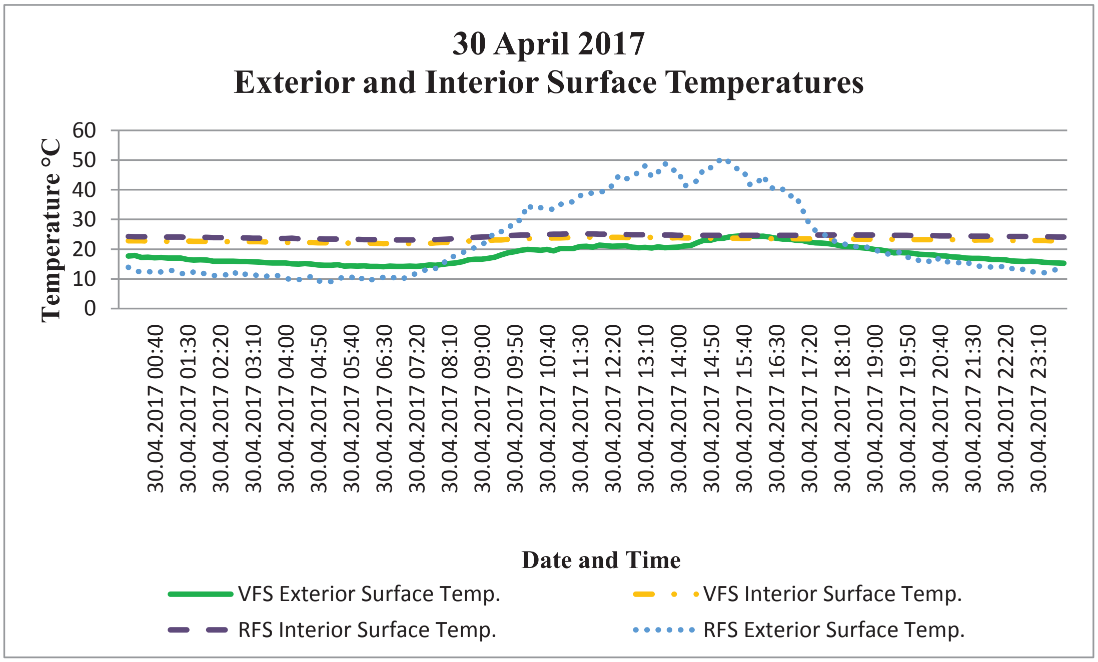


FIGURE 36. Exterior and interior surface temperatures of reference and vegetated facades on August 12, 2017.

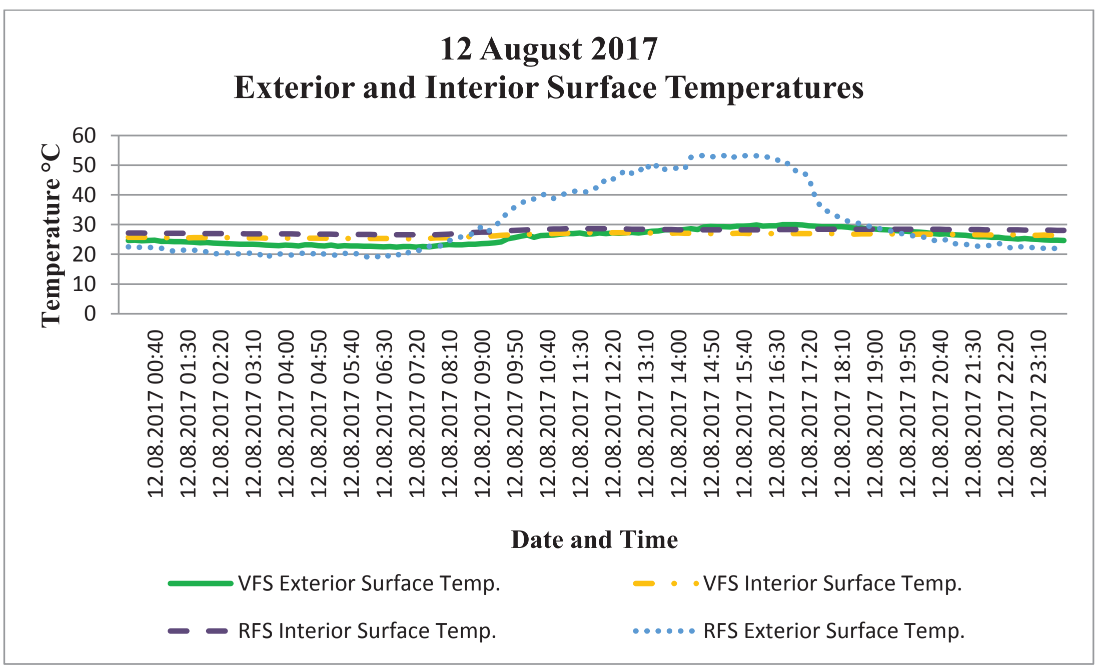


FIGURE 37. Exterior and interior surface temperatures of reference and vegetated facades on September 24, 2017.

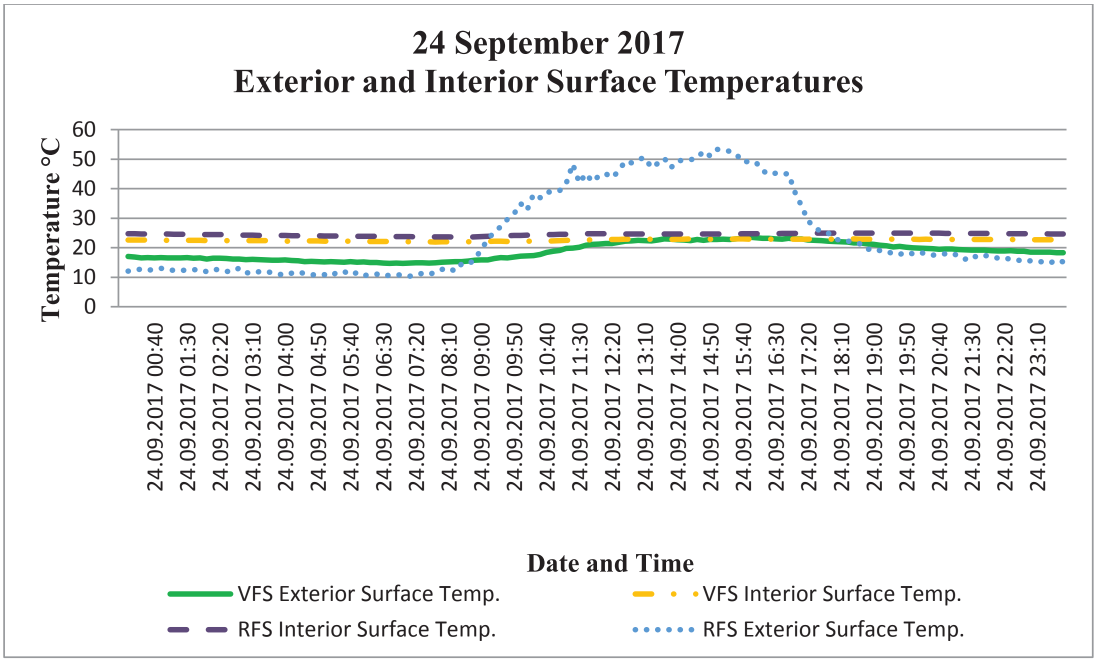
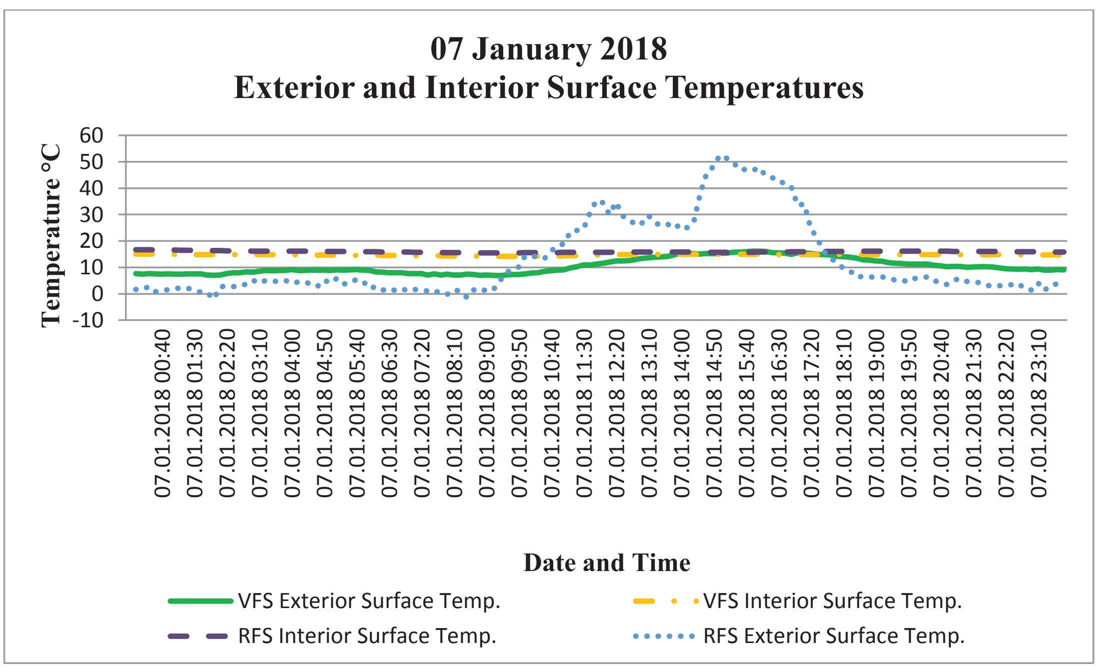


FIGURE 38. Exterior and interior surface temperatures of reference and vegetated facades on September 24, 2017.



interior surface temperatures of reference and vegetated facades were 1.1°C, 1.3°C, 1.8°C and 0.8°C for representative days in spring, summer, fall and winter periods, respectively. Although high differences between the exterior surface temperatures of vegetated and reference walls were observed, there was no significant difference between interior surface temperatures of vegetated and reference walls. This is due to the existing building exterior wall assembly including 5 cm thickness expanded thermal insulation material which enhances the thermal performance of the brick wall.

Also, there was no significant difference between indoor air temperatures behind vegetated and reference walls. The results regarding indoor air temperature differences between vegetated and the reference facade showed similarities with the results of the study conducted under a different climate condition (Cfa: humid subtropical climates) by Chen et al., 2013. Chen et al. (2013) revealed that the cooling effect of VFS on the indoor environment is relatively small because of the high heat resistance and thermal inertia value of the wall [35]. In addition, indoor air temperatures behind both facades were evaluated according to ISO 7730:2005 Standard and ASHRAE Standard 55-2010. Figure 21 and Figure 22 indicate that for representative summer day and respective hours, indoor air temperatures behind both facades were not in the range of 23–26°C, which is recommended as a comfort range for a cooling period in ISO 7730:2005 Standard and ASHRAE Standard 55-2010 [36,37]. Also, Figure 33 and Figure 34 indicate that for a representative winter day and respective hours, indoor air temperatures behind both facades were not in the range of 20–24°C, which is recommended as a comfort range for a heating period in ISO 7730:2005 Standard and ASHRAE Standard 55-2010 [36,37]. Nevertheless, indoor air temperatures behind the vegetated facade were in the comfort range for representative days and respective hours in spring (Figure 15 and Figure 16) and fall periods (Figure 27 and Figure 28), while indoor air temperatures behind the reference facade were not in the comfort range on these days. Figure 15 presents that on April 30th the indoor air temperature (25.7°C) behind the vegetated facade is lower than the upper limit value of 26°C, while the indoor air temperature (26.5°C) behind the reference facade is higher than 26°C. Similarly, Figure 27 presents that on September 24th the indoor air temperature (25.1°C) behind the vegetated facade is lower than the upper limit value of 26°C, while the indoor air temperature (26.5°C) behind the vegetated facade is higher than 26°C. In this case, the vegetated facade system is applied on a non-insulated wall, and it is clear that the decrease in the exterior surface temperatures of the vegetated wall will affect the interior surface temperatures of the vegetated wall and indoor air temperatures behind the facade more dramatically.

Solar reflectance of the reference facade was 2.5–8 times higher than solar reflectance of the vegetated facade. Although solar reflectance of the reference facade was higher than the solar reflectance of the vegetated facade, the exterior surface temperature of the vegetated facade was significantly lower than the exterior surface temperature of the reference facade. That is because the vegetated facade system transfers less energy to the exterior wall of the building even though the vegetated facade system absorbs more solar radiation compared with the reference facade system. Thus, it can be claimed that the vegetated facade system uses most of the energy reaching its surface and so transfers lesser amount of energy to the exterior wall surface of the building wall. Also, the lower solar reflectance values of the vegetated facade indicate that vegetated facade systems have a positive impact on reducing the urban heat island effect.

In addition, the exterior surface temperature fluctuation of the vegetated facade throughout the day was lower than the reference facade. The exterior surface temperatures of the vegetated wall ranged between 14.1°C–24.6°C, while the reference facade ranged between

9.1°C–50.8°C on a representative day for the spring period (Figure 35). Exterior surface temperatures of vegetated wall ranged between 22.4°C–30°C while the reference facade ranged between 18.6°C–53.2°C on a representative day for the summer period (Figure 36). On a representative day for the fall period, the exterior surface temperatures of the vegetated wall ranged between 14.7°C–23.6°C while the reference facade ranged between 10.3°C–53.3°C (Figure 37). Exterior surface temperatures of the vegetated wall ranged between 6.9°C–16.2°C while the reference facade ranged between –2°C–52.6°C on a representative day for the spring period (Figure 38). These results reveal that vegetated facade systems offer a positive contribution in terms of extending the lifespan of a building's exterior wall.

5. CONCLUSION

It can be concluded that a felt type vegetated facade system decreases exterior surface temperatures of an insulated existing wall located in Csa climate in day time during spring, summer, fall and winter periods. This result suggests that VFS has a positive contribution to the thermal performance of a building wall during cooling period thanks to its shading behavior and evapotranspiration effect. However, since heat gain is expected through the building facade in winter, a shading effect is not desired during the heating period. Nevertheless, in nighttime the exterior surface temperatures of the vegetated facade were always higher than the exterior surface temperatures of the reference facade in all cases during each season. This result indicates that VFS has a positive contribution to the thermal performance of a building wall in nighttime during the heating period, while this behavior is not desirable in nighttime in summer. Although differences between exterior surface temperatures of vegetated and reference walls were extremely high for each season, differences between interior surface temperatures of vegetated and reference facades were not remarkable. That is because the existing building exterior wall assembly includes 5cm thick expanded polysytyrene thermal insulation material which enhances the thermal performance of the brick wall. Also, differences between indoor air temperatures behind reference and vegetated facades were negligible. In addition, indoor air temperature was not suitable according to comfort temperature ranges indicated in ASHRAE 55 and ISO 7730 Standards for representative summer and winter days. Nevertheless, indoor air temperatures behind the vegetated facade were in the comfort range in the fall and spring representative days which required cooling, while indoor air temperatures behind the reference facade were not in the comfort range on these days. If the existing exterior wall was designed without any thermal insulation (with poor heat resistance value), it is obvious that the VFS would present a greater passive cooling and heating effect.

It is expected that this study will guide architects, landscape architects, academicians, facade engineers and consultants, governments, ministries and all building construction decision makers at the international and national level. In addition, it is assumed that the results of this study will shed light on national and international targets and strategies regarding the reduction of greenhouse gas emissions until 2030. For further studies it is recommended that net energy (total cooling and heating energy) benefits should be determined. It is also recommended that measurements regarding the thermal performance of a vegetated facade system which is applied on an exterior wall and used as an integrated facade component or VFS with closed air gap should be done. This suggestion was made also in another study claiming that further studies should be done on VFS with closed air gaps (Coma et al., 2017). Also, the cooling and heating effects of a vegetated facade system directly applied on a wall with different thickness of insulation and without insulation should be presented. Thus, possible contribution of VFS in reducing insulation thickness might be determined.

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