Conference Proceedings of 5th International Conference on Countermeasures to Urban Heat Islands (IC2UHI) 2019
December 2-4, 2019, Hyderabad, India

https://doi.org/10.37285/bsp.ic2uhi.34

Effects of the Green Façade on Thermal Comfort in the Transitional Spaces: Field Measurements in Munich, Germany

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ABSTRACT

As a countermeasure to the high-density urbanization and urban heat island, urban green infrastructure has been promoted as an approach to improving human health and adapting to climate change. However, after rapid development in recent years, some high-density areas even lack green space in neighborhoods. In response to the limitation of green land and soil condition in some extreme urban space, planting the climbing plants strategically in both urban and building environment reveals a potential for increasing canopies and optimizing the pedestrian thermal comfort. This paper attempts to test the climbing plants façades', which are defined as green façades, effects on human thermal comfort in a dormitory building in Munich, Germany. Field measurements were set up with a toolkit to record the indices of micro-climate on the different floors of the test building alternately in order to compare the thermal environment of the shaded and unshaded area. Results reveal that the green façades reduced global solar irradiation, globe temperature, and air temperature significantly in typical summer days due to the shading effect. However, as a result of the dragging effect, the green façades also reduced wind flow velocity and influenced on the optimization of thermal comfort in the shaded area. This paper reveals the potential of improvement for thermal comfort in a transitional space via applications of green façades. Further studies would be taken in the urban environment in the future as well.

KEYWORDS

Green façade, Climbing plants, Transitional space, Human thermal comfort, UTCI

Introduction

Rapid urbanization in recent years has caused a sequence of problems such as urban heat island (UHI), urban noise, and air pollution and increased harms to human health. As one of the countermeasures, urban green infrastructure (UGI) including natural areas, farmland, and green space has been promoted as an approach to reducing the ecological footprint, improving human health and well-being, and adapting to climate change (Pauleit et al. 2017). However, some high-density urban neighborhoods even lack space for green and open space. In the urban canyon level, some extreme conditions such as harden pavements, power or water supply pipes, and soil containers also limit the environment for tree growing.

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In response to the limitation of green land and soil condition, planting climbing plants strategically in landscape and building design reveals a potential for increasing canopies and optimizing the pedestrian thermal comfort in the high-density area (Figure 1). On the perspective of building design, strategies of training and guiding the climbing plants on building façade are defined as green facades (GFs). GFs and living wall system (LWS) are two technologies of the green wall (GW) (Perini 2011). Compare to the LWS, which normally constitute with a structure system, soil and plant containers or a substrate layer, and an irrigation and drainage system, the GFs are much more simple and low-cost technologies constituting with a training or guiding structure, a soil container (or planting on ground directly), and an irrigation and drainage system (Coma et al. 2017; Perini and Rosasco 2013).

In application, the GFs are applied not only on the external walls but also on the edge of some transitional spaces such as corridors, arcades, and balconies. In-between the outdoor and indoor space, the transitional space provides a better thermal comfort environment for human beings due to the solar irradiation shielding (Chun, Kwok, and Tamura 2004). On this aspect, there is a potential to provide a better outdoor thermal comfort environment via the combination with the GFs and the transitional space.

Thus, in order to obtain a better understanding on the effects of GFs and the optimization on human thermal comfort, field measurements were set up with a toolkit to record the indices of micro-climate in a test building in summer.

a. Climbing plants guiding by steel structure in MFO park, Zurich, Switzerland

b. Climbing plant forms a canopy with guiding structure

c. Climbing plants shade a street, Guangzhou, China

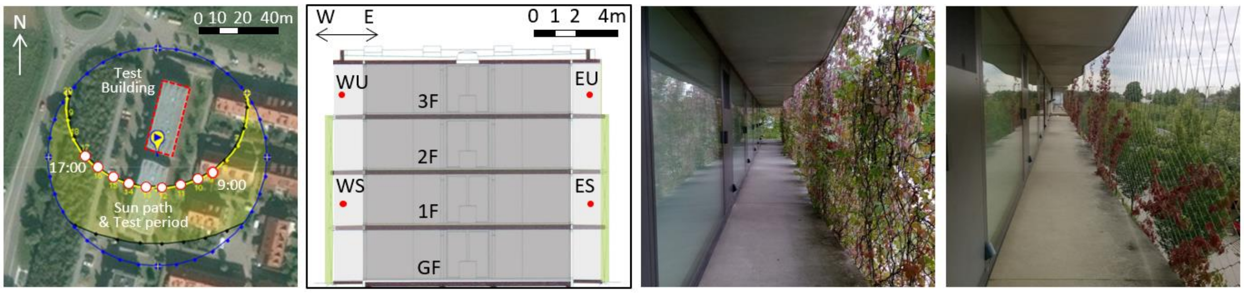
d. GFs with stainless steel rope (case study building in this paper), Munich, Germany

Figure 1. Scenarios of applications with climbing plants in landscape, urban, and building design. *Source*: a. Burckhardt+Partner 2019; b. Zimmermann 2011; c, d. Photographed by author.

Methodology

The field measurements of this study were taken in a student dormitory at Garching of Munich, Germany (humid continental climate, Köppen classification: Dfb) (Köppen 1884). The building locates at the boundary of a residential neighborhood and the long façades are orientated to east-west. There are some 2 floors residential buildings in distance of 14m on the east side and farmlands on the west-north side. The test building is 4 floors in height. Rooms lie on the inner side with around of external corridors, which are enclosed by stainless steel wire ropes. Climbing plants of ivies were planted directly in the earth around the building facades and trained to grow along with the wire ropes. Canopies of the climbing plants have already formed a screen from the ground floor to the 2nd floor on all the orientations in recent years (the building was constructed in 2005, Figure 2).

The field measurements were separated into two typical summer days for both global solar irradiation (Ga) and thermal comfort indices measuring. A moveable toolkit with sensors was set alternately in the middle of the corridors with the distance of 0.7 m to the facades and the height of 1.1 m on the 1st floor (shaded with the GFs) and the 3rd floor (unshaded). On 10th July. 2018 the toolkit was just set on the west façade, then on 11th July. 2018 it was shifted from the east façade to the west façade after 13:00 and collected two groups of data to compare (Table 1).



a. Sun path overlapping on a GoogleEarth satellite photo for the test building

b. Section of the building an d the positions of test points

c. Corridor on 1st floor which was shaded by the GFs

d. Corridor on 3rd floor which was unshaded

Figure 2. Layout of the case study building, positions of test points, and photos of the corridors (ES, east and shaded; EU, east and unshaded; WS, west and shaded; WU, west and unshaded). *Source*: a. Sun Earth Tools 2019; b. Author's diagram based on the section of the building, which was collected from FJGAS 2019; c, d. Photographed by author.

Table 1. Instruments of the moveable toolkit

Instrument	Range	Accuracy	Freq	Duration	Position
LI-1500 Light Sensor Logger with LI-200R Sensor	Ga: Max. 3000 W/m^2	Ga: ±3% (within ±60 ° of incidence)	30 s	8:45-16:30, 10th July. 2018	West facade
Testo-480 with probes:			30 s	9:00-17:00, 11th July. 2018	9:00-13:00, East façade; 13:00-17:00 West facade
a. Humidity and temperature probe	Ta: -20 to +70℃	Ta: ±0.2°C (+15 to +30°C) ±0.5°C (remaining range)			
	RH: 0 to +100%	RH: ±(1.0% + 0.7% of m.v.) (0 to 90 %) ±(1.4% + 0.7% of m.v.) (90 to 100 %)			
b. Comfort probe	Va: 0 to +5 m/s	Va: ±(0.03 m/s + 4% of m.v.)			
c. Globe probe Ø 150mm	Tg: 0 to +120°C	Tg: Class 1			

* m.v., measurement value; Ga, Global Solar Irradiation; Ta, Ambient temperature; RH, Relative humidity; Va, Wind flow velocity; Tg, Black globe temperature.

Based on the indices of black globe temperature (Tg), ambient temperature (Ta), relative humidity (RH), and wind flow velocity (Va), which were recorded by the instruments, mean radiation temperature (MRT) and universal thermal climate index (UTCI) were calculated later. According to ISO 7726 Standard (ISO 1998), the equation that is used most frequently (forced convection) is the following, which for the standard globe (D = 0.15 m, diameter of the globe; μ= 0.95, the emissivity of the globe without dimension):

$$\mathrm{MRT} = [(\mathrm{T_g} + 273)^4 + 2.5 \cdot 10^8 \cdot \mathrm{V}_a{}^{0.6}(\mathrm{T_g} - \mathrm{T_a})]^{\frac{1}{4}} - 273 \quad (1)$$

The UTCI aimed for a one-dimensional quantity adequately reflecting the human physiological reaction to the multi-dimensionally defined actual outdoor thermal environment (Fiala et al. 2001). The UTCI values were calculated in a software of BioKlima 2.6 with the input parameters of Ta, RH, Va, and MRT. The base human activities parameters were set as default in the software (Błażejczyk and Błażejczyk 2010).

Results and discussion

Results of global irradiation

Results of Ga data presented a significant change at the time of 14:30. The Ave. Ga of the unshaded area of 14:30-16:30 (Phase.2) was almost 4.5 times to which of 8:30-14:30 (Phase.1). Comparing two measured areas, the Ave. Ga of the shading area was reduced by 70.2% (Phase.1) and 88.4% (Phase.2). As the test points were only set on the west façade on 1st and 3rd floors, the Ga was increased after 14:30 due to the changing sun angle. The sky cloud condition was also collected from online weather data. Data of the hourly sky cloud cover ratio (CCR) and Ave. Ga reflected that before 14:00 even the CCR was at a high level, the Ga value still raised slowly because the sun angle was from south-east and the solar irradiation was blocked by the building itself, respectively, after 14:00 the Ga value increased obviously (Figure 3). The orientation of the building (east-west) influenced the results of the Ga values in the morning.

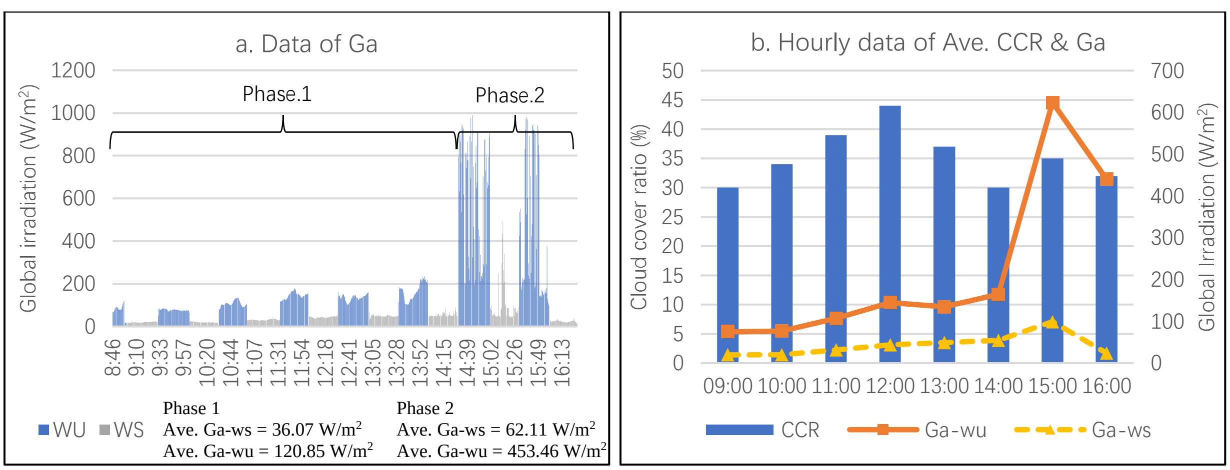


Figure 3. Data of Ga and CCR (Duration: 8:45-16:30, 10th July. 2018; WS, west and shaded; WU, west and unshaded). *Source*: a. Author's field measurement; b. CCR data collected from WWO 2019.

Results of thermal comfort indices

Outdoor environmental weather data was collected and show that the air temperature was stable (Ave. Ta = 17.5℃), the CCR increased after 12:00, and the main wind direction was north-west during the measurement period (Figure 4).

As the test points variated periodically between the shaded and unshaded positions, the trends of the measured results also changed in every half hour. The test points were also set to follow the sun angle and shifted from east to west façade at 13:00 so that the results presented some differences between two orientations (Figure 5). The main results are as follows.

- Comparison on measurements results and the weather data:

The Ga, Ta, and UTCI values were at a higher level, while the Va values were at a lower level before 13:00. It could be explained that the indices followed the variation of the weather data, which show that the CCR was lower and the solar irradiation was higher in the morning, respectively, the measured Va increased in the afternoon when the test points were set on the orientation facing to the main wind direction of north-west.

- Optimization of the human thermal comfort:

Ave. Tg, Ta, MRT, and UTCI of shaded area reduced by 0.8℃, 0.9℃, 1.4℃, and 0.9℃ on the east façade from 9:00 to 13:00, relatively, which increased by 2.2℃, 0℃, 2.7℃, and 0.8℃ on the west façade from 13:00 to 17:00. Ave. Va of shaded area reduced by 0.1 m/s (east) and 0.7 m/s (west) (Table 2). Results reveal that the GFs present potential of optimizing the human thermal comfort indices in the transitional spaces during the higher Ta and lower Va period. As the MRT was calculated basing on Tg, Ta, and Va, the calculation ignored the direct Ga so that it may underestimate the MRT values at where expose to the solar radiation directly, such as the unshaded areas. With the wind flow became stronger in the afternoon, the UTCI was lower in the unshaded than the shaded area. However, some of the Va values in the unshaded area were over 5 m/s in the afternoon, which is over the threshold of wind comfort for human beings (Stathopoulos 2009).

- Comparison on the shaded and unshaded scenarios:

Considering the values variated slowly when the test position changed periodically, the average values of different indices may not reflect the trend of the variation sufficiently. Thus, a further comparison of the haft hour data is added (Figure 5.f). Every half hour's average value is compared to the last value of the last measured position. Result reveals that the indices including Tg, Ta, MRT, and UTCI followed the decreasing trend during the shaded period. The average reduction of thermal comfort indices in the shaded period is 11.4℃ (MRT) and 2.0℃ (UTCI), respectively, the maximum reduction is 32.7℃ (MRT) and 7.9℃(UTCI). Through shifting the test positions between the shaded and unshaded area and following the sun path, the measurements reflected the shading effect significantly.

- Thermal comfort in the transitional space:

Comparing to the UTCI category (Broede 2013), results presented that 52.4% of the UTCI values were at the "no thermal stress level (+9 to +26℃)" and 39.4% of which were at the "moderate thermal stress level (+26 to +32℃)". All the transitional space in the test project presented a thermal comfort condition during the measurement period.

Regression and correlation analysis

Regression and correlation analysis for UTCI with other parameters reveal that Tg and MRT have higher correlations with UTCI, while Ta and Va present lower R^2 and correlation values (Figure 6 and Table 3). Results also show that the R^2 for Tg and MRT with UTCI are higher in the morning when Ave. Va is lower. Correlation for Va and UTCI is higher in the shaded area and implies that the GFs reduced the Va on both façades and influenced on the UTCI. In this case, even the Ta has been decreased by the shading effect of the GFs, the UTCI values variated much slower so that the correlation for Ta and UTCI was still at a lower level. Thus, in order to improve the wind flow in the corridors, it may need to keep some blanks or voids when forming GFs.

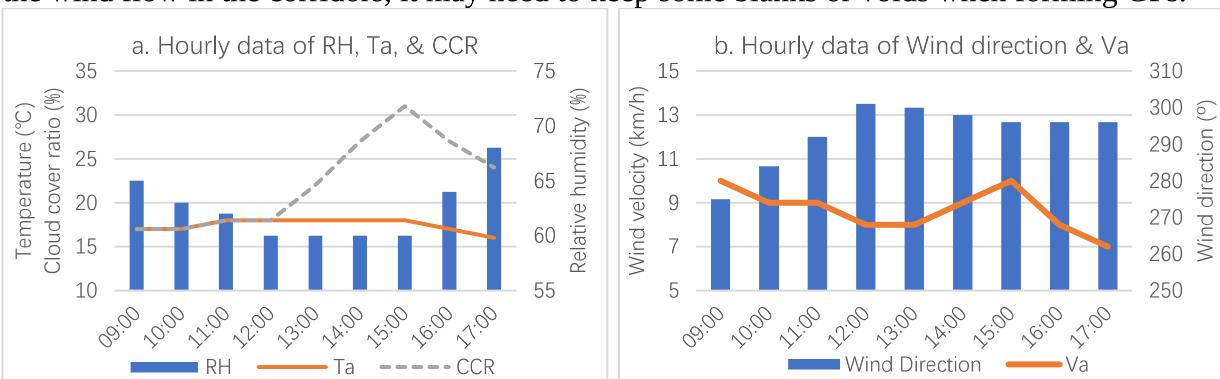


Figure 4. Data of weather station (Duration: 9:00-17:00, 11th July. 2018). *Source*: WWO 2019.

Table 2. Ave., Max., and Min. values of difference indices

Indices		Test points			
		ES	EU	WS	WU
Tg (℃)	Ave.	32.9	33.7	28.9	26.7
	Max.	44.8	45.2	35.4	30.1
	Min.	18.2	17.3	25.6	21.2
Ta (℃)	Ave.	19.4	21.3	18.2	18.2
	Max.	22.8	26.6	20.7	20.9
	Min.	15.2	17.1	16.5	16.8
RH (%)	Ave.	56.3	46.8	56.3	55.9
	Max.	74.3	63.7	66.7	64.9
	Min.	45.9	30.1	45.3	43.2
Va (m/s)	Ave.	0.4	0.5	0.4	1.1
	Max.	1.1	3.1	2.8	5.4
	Min.	0.1	0.1	0.1	0.1
MRT (℃)	Ave.	47.3	48.7	41.4	44.1
	Max.	83.4	93.9	75.1	85.4
	Min.	18.9	14.0	30.2	24.2
UTCI (℃)	Ave.	27.8	28.7	25.5	24.7
	Max.	37.7	39.1	30.6	27.7
	Min.	18.6	18.1	22.3	18.6

* EU, east and unshaded; ES, east and shaded; WU, west and unshaded; WS, west and shaded.

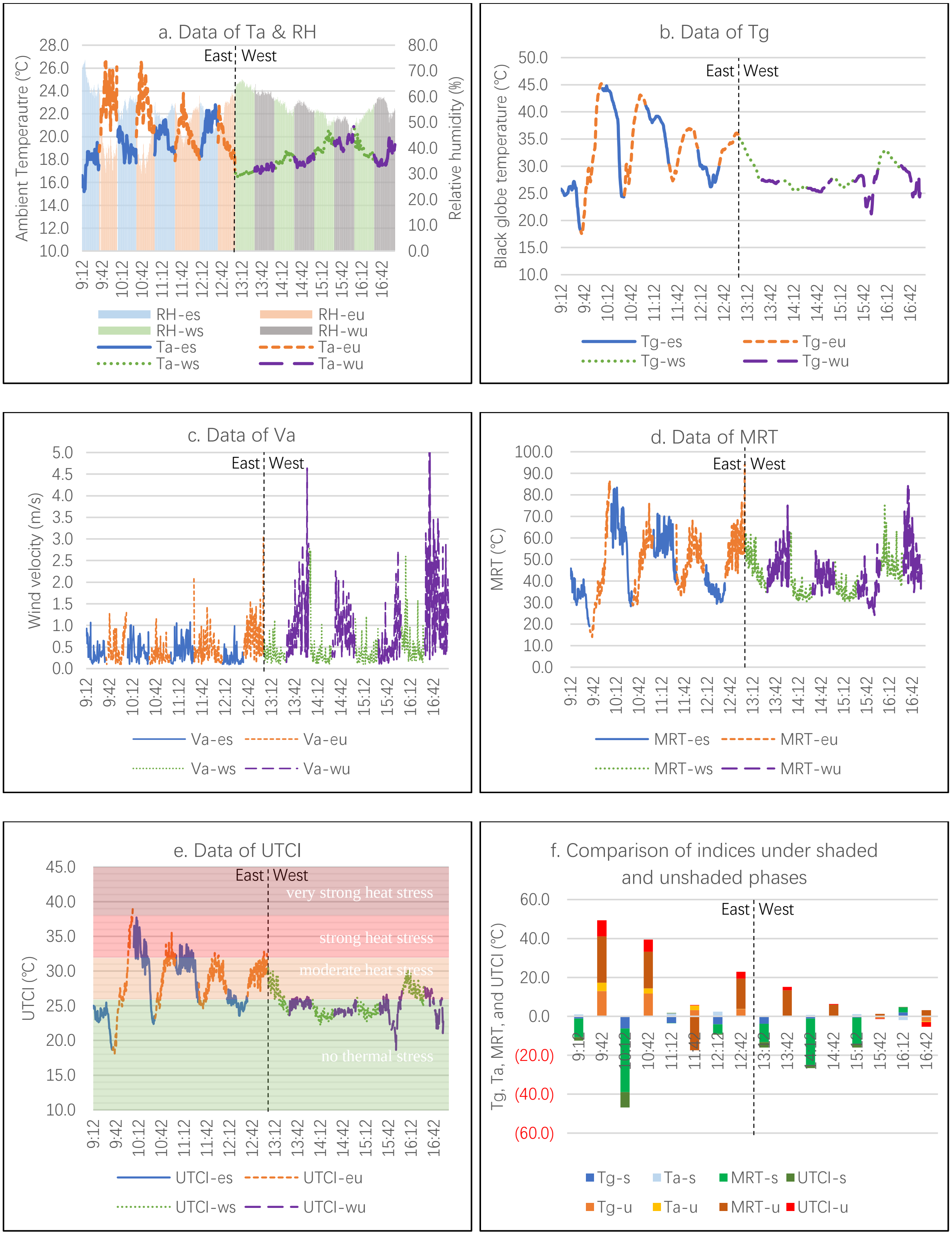
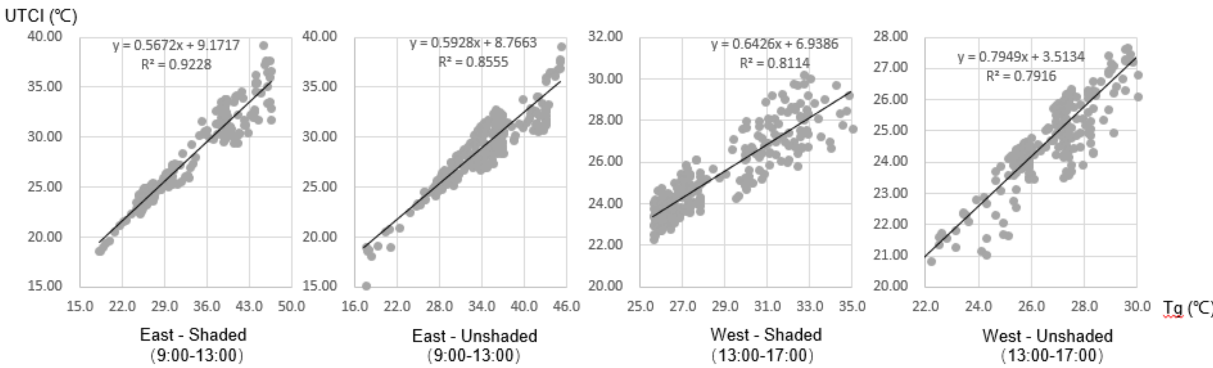
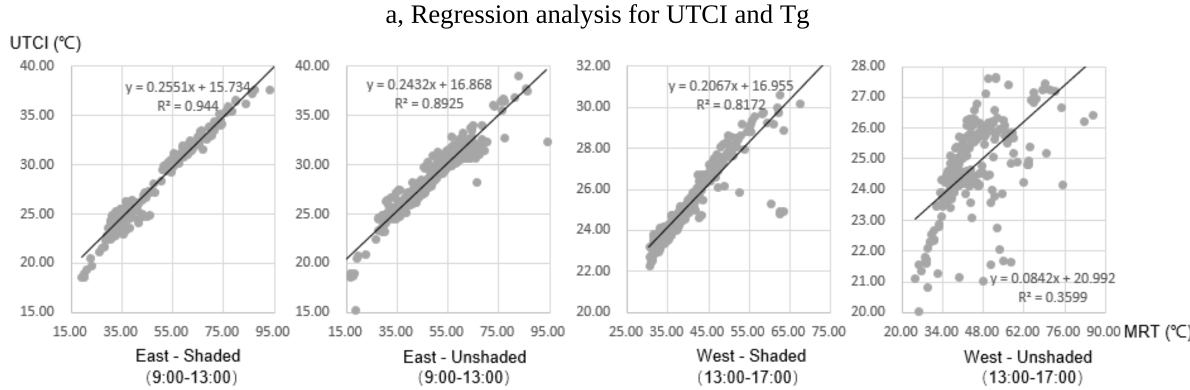


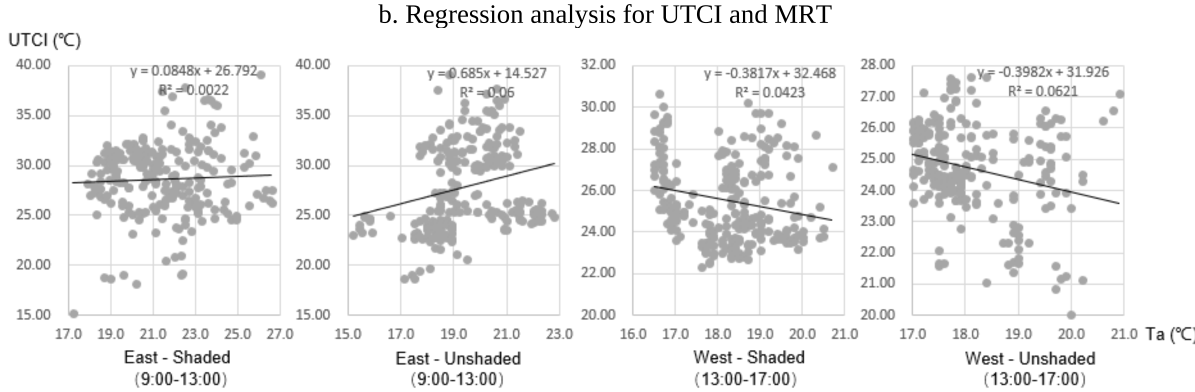
Figure 5. Data of different indices (Duration: 9:00-17:00, 11th July. 2018; Test points were shifted from east to west façade after 13:00 following the sun path; ES, east and shaded; EU, east and unshaded; WS, west and shaded; WU, west and unshaded). *Source*: Author's field measurement.



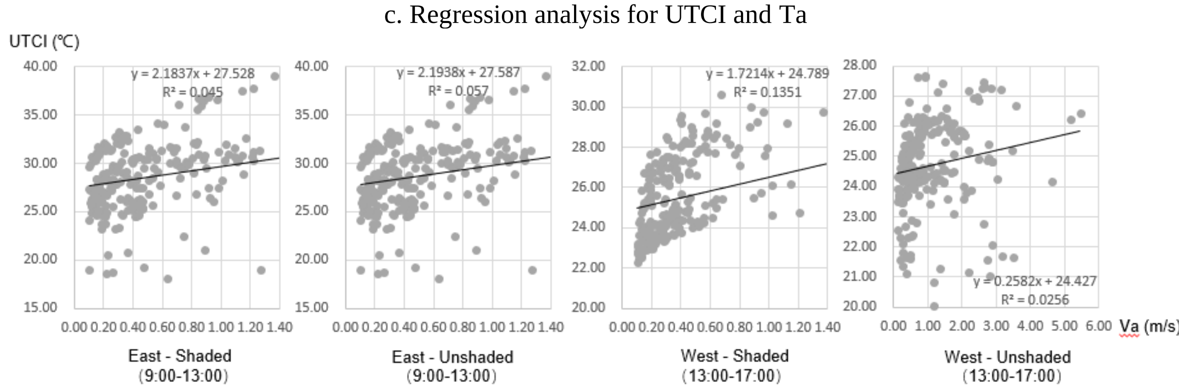
a, Regression analysis for UTCI and Tg



b. Regression analysis for UTCI and MRT



c. Regression analysis for UTCI and Ta



d. Regression analysis for UTCI and Va

Figure 6. Regression analysis for UTCI and different indices. *Source*: Author's field measurement.

Table 3. Correlation analysis for UTCI with different indices

Indices	Test points			
	ES	EU	WS	WU
Tg	0.961	0.926	0.905	0.890
MRT	0.972	0.953	0.903	0.600
Ta	0.245	0.024	-0.205	-0.249
Va	0.436	0.231	0.361	0.160

* EU, east and unshaded; ES, east and shaded; WU, west and unshaded; WS, west and shaded.

Conclusion

Through taking field measurements in the building with external corridors in Munich, Germany in typical summer days, the results reveal that the GFs reduced Ga, Tg, and Ta significantly due to the shading effect. However, as a result of the dragging effect, the GFs also reduced Va and influenced on the optimization of UTCI in the shaded area. This paper reveals the potential for improvement for human thermal comfort in the transitional spaces via the applications of GFs. The average reduction of thermal comfort indices in the shaded period are up to 11.4℃ (MRT) and 2.0℃ (UTCI). As the GFs reduced Ga up to 70-88%, on one side, they could reduce the internal gains for solar irradiation, on the other side, they could decrease the daylight availability of indoor environment in summer as well.

Some limitations of the settings in the field measurements may influence on the results. As the toolkit was only set on different floors in the building, the outdoor environmental data and boundary conditions were not measured but collected from open source weather data. The different height of the test points, which of the shaded and unshaded area is 5.2 m (2 floors), may also influence the results. The evaporation effect of the climbing plants was not discussed in the field measurements because a precise measurement for the canopy was lacked. The leaf area index (LAI) is also lacked to measure and discuss. Thus, some aspects of the study could be improved in future research. Further studies would be taken in the urban environment in the future as well.

Acknowledgments

This research is supported by the State Scholarship Fund of China (No. 201606150060), the National Natural Science Foundation of China (No. B51478188), and the Science and Technology Planning Project of Guangzhou, China (No. B3160760). The toolkit for the field measurements is supported by the Chair of Building Technology and Climate Responsive Design in the Faculty of Architecture, Technical University of Munich (TUM).

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