Building and Environment 76 (2014) 113–124

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

The effects of climbing vegetation on the local microclimate, thermal performance, and air infiltration of four building facade orientations

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A R T I C L E I N F O

Article history:
Received 25 January 2014
Received in revised form
7 March 2014
Accepted 11 March 2014

Keywords:
Green facades
Facade vegetation
Facade thermal performance
Energy-efficient buildings

A B S T R A C T

The use of climbing plants and other vegetation types as part of building enclosures has been shown to improve facade thermal performance under certain conditions, although detailed measurements of the impacts of plants on wall shading and local environmental conditions under multiple orientations in real buildings are currently lacking. Therefore, this article presents results from a series of experiments conducted on bare and ivy-covered sections of four pairs of walls of different orientations on existing university buildings during summer conditions in Chicago, IL USA. Over a period of nine days, the research team monitored how existing plant layers impacted facade exterior surface temperatures, heat flux through the walls, localized outdoor air temperatures, relative humidity, absolute humidity, and air velocity immediately adjacent to the facades. Changes in nearby air temperatures and air velocity were also used to estimate the impact of the vegetation layer on air infiltration under hypothetical airtightness scenarios. The experimental results demonstrated that the ivy layers reduced exterior surface temperatures by an average of 0.7 °C across all facades (12.6 °C hourly maximum), depending on orientation and time of day. The ivy layers were estimated to yield a 10% reduction in heat flux through the opaque walls on average for the duration of the experiment, again varying by orientation and time of day. These findings are consistent with other recent studies. The plant layers also reduced outdoor air temperatures immediately adjacent to the facades by 0.8–2.1 °C, on average and varying with facade orientation. Relative humidity was higher inside the vegetation layers, but absolute humidity was not affected. Finally, the plant layers were also shown to lead to reductions in wind speeds immediately adjacent to the facades (averages ranging from 0% to 43%, depending on facade orientation and the presence of nearby obstructions), which when combined with measured differences in adjacent outdoor air temperature, were estimated to lead to an average reduction in air infiltration rates per unit wall area of 4–12%. Results herein provide further evidence that ivy walls can lead to small energy savings during summer conditions by solar shading and new evidence that additional energy savings may be achieved by reduced air infiltration rates because of the vegetation.

1. Introduction

Climbing plants and shrubs growing directly along building facades or along plant supports such as trellises and wires can have multiple benefits, including improved thermal performance [1–3], improved air quality [4–6], and creating visual interest. The effects that climbing plants can have on facade thermal behavior include reduced surface temperatures due to shading [7,8], air-cooling through evapotranspiration [9], and reduction of wind velocities near the facade [10], which when combined, often leads to lower heat flux through walls [1,8,11]. This can also create a milder local microclimate near the facade, which may be beneficial for mitigating the urban heat island effect [12]. However, data on many of these impacts remain quite limited [13].

Several previous experimental studies reported that facade surface temperatures immediately behind wall vegetation were typically lower during summer conditions by an average of approximately 1–9 °C [8,10,11,14,15], depending on the density of the plant layer and weather conditions during the experiments. Reducing facade surface temperatures reduces conduction through walls, which has been shown to reduce space conditioning energy use and peak electricity demand. For example, Di and Wang [11]

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http://dx.doi.org/10.1016/j.buildenv.2014.03.011
0360-1323/

measured a 28% reduction in the peak-cooling load through a west-facing wall of a building covered with thick ivy on a clear summer day.

Other potentially important effects of facade vegetation are reductions in air temperature and air velocity near the facades. For example, a year-long study monitoring the microclimate conditions near ivy-covered walls found that such walls experienced smaller daily ranges in outdoor air temperatures and relative humidity [14]. Ambient air temperatures near exterior walls covered with ivy were also shown to be 1–3 °C lower than near bare walls in two other studies [7,16], although data remain limited. Reducing air speeds and temperatures near facades may also have additional positive effects by reducing air infiltration, which is driven by differences in wind pressures and air temperatures between the interior and exterior of a building. Air infiltration is responsible for approximately 40% and 15% of heating energy consumption in residential and commercial buildings, respectively [17], and for up to 33% of total energy consumption in residential buildings located in cold climates [18]. Importantly, exterior walls are estimated to be responsible for approximately 35% of total air infiltration into residential buildings [19]. In addition to increased space conditioning loads, air infiltration allows for moisture transfer into the indoor space in hot and humid climates, which may negatively affect indoor air quality and can cause deterioration of materials within building enclosures. However, the impacts of vegetation of air infiltration have not been fundamentally explored to date.

Limited experimental data exist on wind speed reductions by facade plant layers. Perini et al. [10] measured air velocity in the middle of a 20 cm thick layer of English ivy (*Hedera helix*) covering the northwest facade of a two-story brick building in the Netherlands between September and October (however, fewer than 30 min of data were recorded in total). Air velocities measured near the vegetated walls were 84% lower than those measured near the bare walls. Moving farther away from locations immediately adjacent to facades, DeWalle et al. [18] and Mattingly et al. [20] assessed the effect of vegetation windbreaks installed near buildings. They observed that a row of trees placed in front of small buildings in cold climates resulted in a 29–48% reduction in wind speed, corresponding to an estimated 30–54% decrease in air infiltration. The porous landscape elements (e.g., trees, shrubs, and plants) were also more effective in reducing air velocity than solid barriers, and tended to break down eddies resulting in a more even wind pressure distribution on the facade [18,19].

Although many of these impacts of ivy walls have been addressed in some level of detail, measurements are often limited by the number of facades and orientations explored, were conducted over a short period of time, or have not been assessed all in the same setting [13]. Therefore, the purpose of this study is to experimentally evaluate how climbing plants affect facade thermal performance and facade microclimate conditions (including outdoor air temperature, relative humidity, and air velocity) using simultaneous measurements on exterior walls of four ivy-covered buildings (with four different orientations) during the summer in Chicago, IL, USA. Results are also used to estimate reductions in heat flux through the measured walls and to model likely reductions in air infiltration through the building enclosures covered with vegetation. This study was conducted as part of the planning phase for a major capital renewal project of campus academic buildings initiated by the Planning and Design group of the University of Chicago Facilities Services.

2. Methodology

The experiment consisted of measuring the thermal performance of four building facades, one of each facing east, south, west, and north. The buildings were located on the campus of the University of Chicago, located in the cold climate of ASHRAE Zone 5. The measured buildings included Culver Hall (east facade), the Anatomy Building (south facade), the Zoology Building (north facade), and the Erman Biology Center (west facade), which form a square semi-enclosed courtyard as shown in Figs. 1 and 2. Each four-story tall building constructed in the 1890s was built with heavy masonry exterior walls. The facades were composed of 30 cm load-bearing brick clad with 12.5 cm limestone panels and 1.3 cm interior plaster finish. The east, west, and south facades were all located 10–20 m away from nearby trees and other large objects that could distort the measurements. However, the north facade was shielded by the trees located 2–3 m away from the wall, which may have influenced some of the results herein.

Each building was covered with a ~20 cm thick layer of Boston ivy (*Parthenocissus tricuspidata*). All buildings had a similar level of foliage coverage with a leaf area index (LAI) of approximately 2 (estimated visually). Two exterior areas were selected for the measurements on each facade: (1) an area densely covered with plants and (2) an immediately adjacent area without plants. The bare and vegetated facade areas were located within 2–3 m from each other at the same height along the wall. This horizontal distance from each other was chosen to capture similar outdoor environmental conditions on both bare and vegetated facades while simultaneously minimizing three-dimensional heat transfer effects. The measured areas were located at the first floor level (approximately 3 m from the ground) in the case of the east, south, and west facades and at the second floor level (approximately 6 m from the ground) for the north facade. The interior spaces behind the measured facades were air-conditioned office spaces.

The experiment measuring properties of the bare and vegetated facades was conducted during nine summer days from July 9 until July 18, 2013. The following parameters were measured during the experiment at 1-min intervals:

- Direct solar radiation on a horizontal surface at the south facade only (for general characterization of solar radiation throughout the day).
- Solar radiation incident on the vertical surface at the south facade only.
- Outdoor air temperature and relative humidity near the bare and vegetated facades (approximately 5 cm away from the wall).
- Indoor air temperatures and relative humidity in each room.
- Surface temperatures of the bare exterior facades.

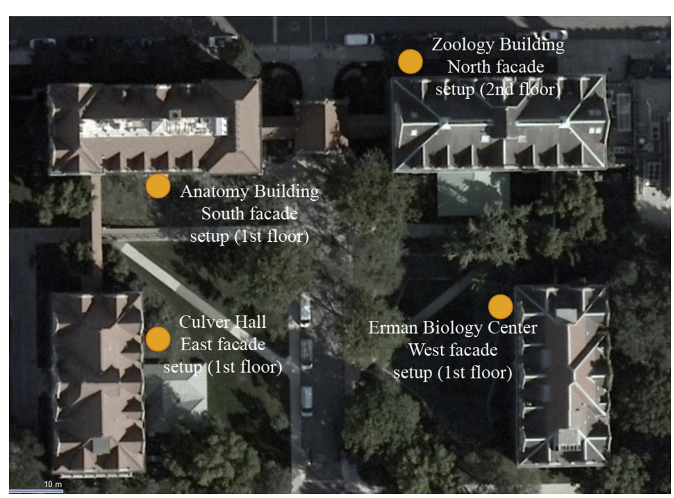

Fig. 1. Experimental setup at the University of Chicago.

Fig. 2. An example of a measured building (south facade of Anatomy Building) (left) and a detailed setup view (right).

- Surface temperatures of the vegetated exterior facades (behind the plant layers).
- Surface temperatures of the interior walls behind both the bare and vegetated facades.
- Air velocity near the bare and vegetated facades (approximately 15 cm away from the wall).

Outdoor air temperature and relative humidity were measured near the facade using Lascar EL-USB-2 humidity and temperature data loggers (±3% accuracy for RH and ±0.5 °C accuracy for air temperature). Surface temperatures were measured with Lascar EL-USB-TC thermocouple data loggers using self-adhesive patch Type K thermocouples with miniature plugs (±0.5 °C accuracy). Direct solar radiation on the horizontal surface was measured using an Onset HOBO weather micro-station with a pyranometer sensor (±10 W/m^2 or ±5% accuracy, whichever is greater in sunlight); the sensor was attached to a bracket installed on the south facade only (the Anatomy Building). The solar radiation incident on the vertical surface was measured with a Kipp&Zonen SMP3 pyranometer (±3% accuracy) directly attached to the exterior wall of the south facade only. Air velocity was measured 15 cm from the facade with Cambridge ACCUSENSE F900-O-5-1-0-2 air velocity sensors (±5% reading or ±0.05 m/s accuracy). The measurements of vertical solar radiation and air velocity on the south facade were recorded using HOBO U12 data loggers with external ports.

The experiment was conducted during eight summer days in Chicago during which the mean air temperature and relative humidity were 27 °C and 61%, respectively, using data retrieved from Midway Airport [21]. Air temperatures reached as high as 35 °C and as low as 15 °C during the experimental campaign. The majority of the experimental days were sunny, with maximum amounts of horizontal solar radiation of 800 W/m^2 or greater on eight of the nine days of measurements. Weather conditions during the experimental campaign are summarized in Table 1. The measured interior office rooms were occupied during normal office hours with the thermostat set point temperature of 24 °C. Only data from a six-day period between July 10 and 15 with all equipment were properly functioning are shown in this work; however, these days are sufficiently representative of all measured conditions.

3. Experimental results

The following sections describe experimental results from the campaign, including impacts on wall surface temperatures, heat flux, outdoor air temperatures, relative humidity, absolute humidity, wind speed, and modeled air infiltration.

3.1. Wall surface temperature

The surface temperature of the bare and vegetated facades was measured on the exterior and interior of the building walls facing four different orientations. Those temperatures were then used to calculate surface temperature gradients for each facade (i.e., the exterior surface temperature minus the interior surface temperature, which serves as a surrogate for heat flux given constant thermal resistance values for the walls). Fig. 3 and Table 2 summarize the facade surface temperatures and surface temperature gradients measured during the experiment. Fig. 3 also shows the ambient air temperature and direct solar radiation on a horizontal surface during the experiment. Hourly averages are provided for minimum and maximum values to smooth extreme variations and provide more meaningful results. One should note that surface temperature data were lost for the interior surface of the plant-covered west wall due to instrumentation failure during the majority of the experiment. However, data from the other interior wall measurements revealed that the surface temperatures of the interior wall behind

Table 1
Weather conditions during the experiment.

Date	Air temperature (°C)[a]			Relative humidity (%)[a]			Wind speed (m/s)[a]			Solar radiation (W/m^2)[b]
	Min.	Mean (±s.d.)	Max.	Min.	Mean (±s.d.)	Max.	Min.	Mean (±s.d.)	Max.	Max.
10-Jul	20.6	25.7 (±2.7)	30.6	48	65.8 (±14.0)	88	1.6	3.7 (±1.4)	6.2	879
11-Jul	17.8	22.6 (±3.0)	26.7	34	50.9 (±17.7)	80	0.0	3.4 (±1.7)	5.7	879
12-Jul	15.6	22.8 (±3.9)	27.8	34	52.0 (±15.3)	78	0.0	2.3 (±1.7)	5.1	909
13-Jul	19.4	24.3 (±2.9)	27.8	39	55.4 (±11.9)	75	0.0	3.2 (±1.7)	5.7	889
14-Jul	22.8	26.5 (±2.8)	30.6	49	62.8 (±9.9)	76	0.0	3.8 (±1.3)	6.2	839
15-Jul	23.9	27.8 (±2.5)	31.7	53	68.7 (±9.0)	84	0.0	2.8 (±1.8)	7.2	979
16-Jul	25.0	29.5 (±2.9)	33.3	47	62.6 (±12.0)	82	1.6	3.2 (±1.3)	5.7	917
17-Jul	25.6	30.2 (±3.1)	34.4	41	58.3 (±12.1)	76	1.6	3.2 (±1.2)	6.7	874

[a] Weather data for Midway Airport (source: wunderground.com).
[b] Direct solar radiation on a horizontal surface measured during the experiment.

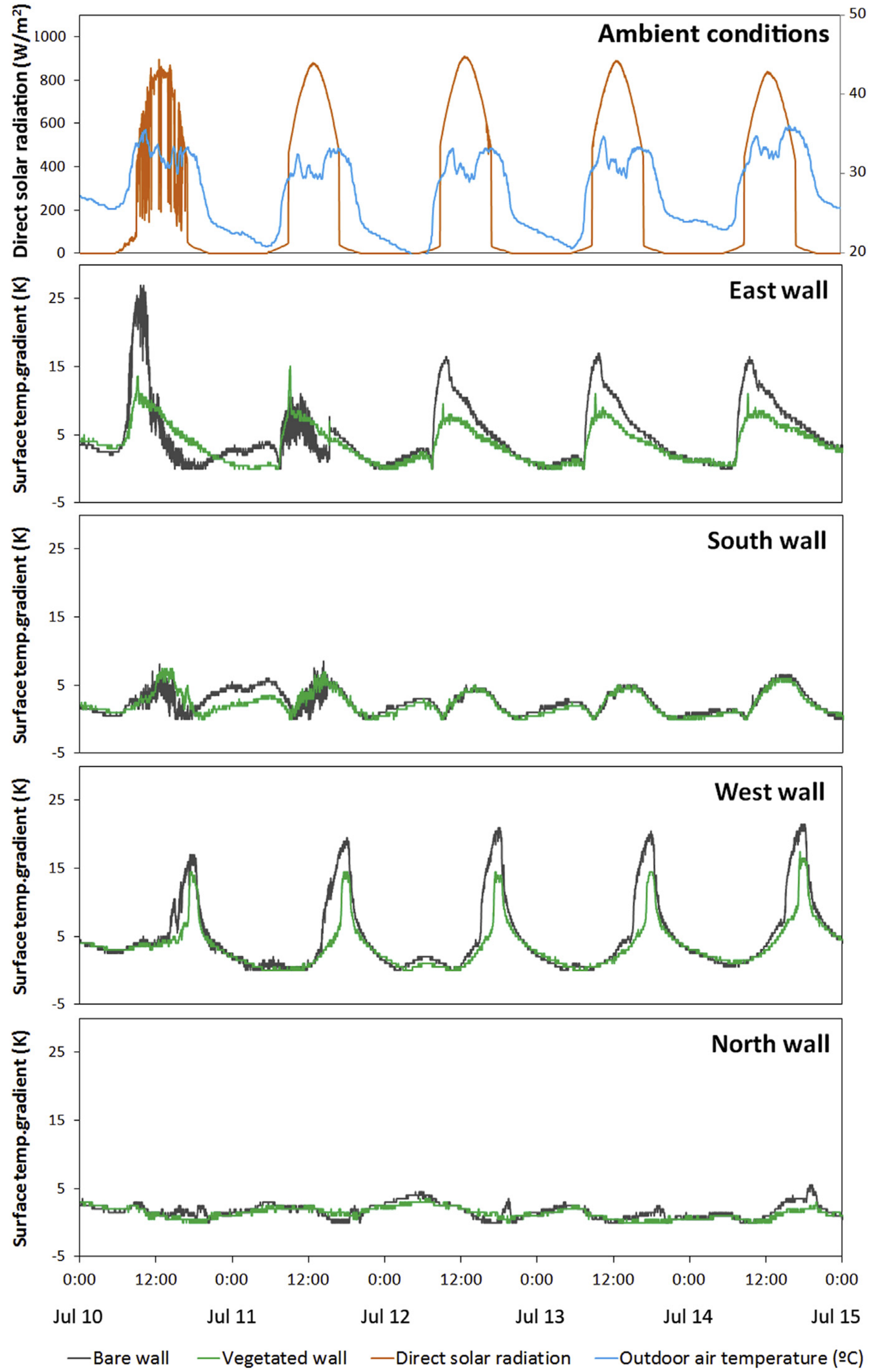

Fig. 3. Surface temperature gradient of the east, south, west, and north walls during July 10–15, 2013.

the bare and vegetated facades were very close (within approximately 0.3 °C of a mean of 24.5 °C during all periods); therefore, the assumption was made for further calculations that these temperatures are equal, which is reasonable for the air-conditioned interior.

The exterior surface temperature of the wall immediately behind the plant layer was consistently lower than that of the bare wall for most facade orientations. The average bare facade exterior surface temperature varied between 26.8 °C (north) and 29.5 °C (west), and the average vegetated facade exterior surface temperature varied between 26.2 °C (north) and 28.7 °C (west). This was primarily due to the plant layer reducing the hourly maximum facade exterior surface temperatures, from as much as 46.9 °C to 35.9 °C on the east facade. The mean reduction of the facade exterior surface temperatures ranged between −0.1 °C and 1.2 °C, and reached as high as 12.6 °C on the east facade. The exterior temperatures of the plant-covered facades were, however, higher than the bare facades during nighttime periods, likely because the vegetative layer prevented nighttime cooling of the wall by long wave radiation to the sky and/or convection to the outdoor air. The reduction in the facade surface temperature and facade gradient of the vegetated walls were statistically significant for all measured values with $p < 0.0001$ (calculated using a t-test in Stata Version 12).

The largest surface temperature reductions between the bare and ivy-covered exterior walls corresponded with the peak

Table 2
Facade surface temperatures and temperature gradients measured during the experiment.

	Exterior surface temperature		Interior surface temperature		Exterior-interior surface temperature gradient		Reduction in exterior surface temperature (°C)	Reduction in ex-int surface temperature gradient (°C)
	Bare (°C)	Veg. (°C)	Bare (°C)	Veg. (°C)	Bare (°C)	Veg. (°C)		
East wall, number of observations = 12,481								
Mean (±s.d.)	29.5 (±5.9)	28.3 (±3.5)	23.0 (±0.3)	23.3 (±0.3)	6.5 (±5.9)	5.0 (±3.4)	1.2 (±3.1)	1.5 (±3.1)
Hourly max.	46.9	35.9	23.5	24.0	23.5	11.9	12.6	12.8
Hourly min.	19.8	21.4	22.5	22.6	−3.3	−2.0	−3.9	−3.8
South wall, number of observations = 12,481								
Mean (±s.d.)	27.6 (±3.6)	27.7 (±3.0)	25.3 (±0.7)	24.8 (±1.1)	2.3 (±3.7)	3.0 (±3.6)	−0.1(±1.0)	−0.6(±1.0)
Hourly max.	35.7	34.8	26.5	26.2	11.8	12.5	1.8	1.5
Hourly min.	19.9	22.0	23.3	21.3	−5.6	−3.3	−3.4	−3.5
West wall, number of observations = 12,481								
Mean (±s.d.)	29.6 (±5.0)	28.7 (±3.3)	24.4 (±0.4)	24.4 (±0.4)[a]	5.2 (±4.8)	4.3 (±3.1)[a]	0.9 (±2.4)	0.9 (±2.4)
Hourly max.	45.1	39.3	25.5	25.5	20.6	14.8	11.1	11.1
Hourly min.	22.0	23.0	23.9	23.9	−2.0	−1.0	−1.1	−1.1
North wall, number of observations = 12,481								
Mean (±s.d.)	26.8 (±3.1)	26.2 (±2.7)	25.5 (±0.6)	25.2 (±0.6)	1.3 (±1.7)	0.9 (±2.3)	0.7 (±0.8)	0.4 (±0.9)
Hourly max.	34.0	31.8	27.0	26.7	7.6	5.8	3.0	2.8
Hourly min.	20.8	21.5	24.5	24.5	−4.2	−3.1	−0.7	−1.2

[a] The interior surface temperature for both vegetated and bare parts of facade was assumed to be equal.

exposure to solar radiation for each facade. The largest surface temperature reduction was observed on the east and west facades that are exposed to high intensity solar radiation in early morning and late evening hours at the low sun angles, respectively. This suggests that planting vines alongside these facade orientations may be more beneficial for improving facade thermal performance relative to north and south orientations, which experienced smaller peak and average reductions.

An additional measure of the impact of the plant layers on facade thermal performance is the temperature gradient from the exterior to interior surfaces. The temperature gradient of the vegetated facade was typically lower than that of the bare facade, particularly for most daytime periods, but ranged in magnitude depending on facade orientation. The mean reduction in the exterior–interior wall temperature gradient varied between 0.4 °C (north), −0.6 °C (south), 1.5 °C (east), and 0.9 °C (west), and reached an hourly maximum reduction of 12.8 °C for the east facade and 11.1 °C for the west facade.

A linear regression analysis was also performed to explore the difference in the surface temperature gradients between the bare and vegetated facades for both daytime and nighttime periods, as shown in Fig. 4. The regression results are intended to allow for prediction of the facade temperature gradient of a plant-covered wall if the bare facade temperature gradient is known. As shown in Fig. 4, the reduction in the surface temperature gradients of the plant-covered walls strongly depends on facade orientation and daytime versus nighttime periods. For the east- and west-facing walls, the regression line slope is approximately 0.5 during daytime, suggesting that the vegetated facade surface temperature gradients were only half that of the bare facades when exposed to direct sunlight in the mornings and evenings. For the north- and south-facing walls, which are not directly exposed to the sunlight, the regression line slope approaches 1, showing that the surface temperature gradients of the bare and vegetated walls on these orientations are similar. At nighttime, the walls of all orientations perform approximately the same with little difference in temperature gradient between the bare and vegetated walls (with a regression slope near 1). Additionally, the intersection of the regression lines with the 1:1 line for all facades (except south) occurs when facade surface temperature gradients are lower than 5 °C, which means that the temperature gradient reduction due to a plant layer is most meaningful when the bare wall temperature gradient is 5 °C or higher.

As the wall construction assemblies of all facades were the same, the effect of the plant layer on heat flux through each wall can also be estimated using the temperature gradient measured across the exterior wall [1]. Therefore, the temperature gradients between the exterior and interior surfaces were estimated separately for bare and vegetated walls at each location using the measured surface temperatures. Once the average difference between the facade temperature gradients for the bare and vegetated facades was known, the reduction in heat flux through the exterior wall due to the plant layer was calculated using Eq. (1).

$$\frac{Q_{bare}-Q_{veg}}{Q_{bare}}=\frac{\frac{(T_{ext\ bare}-T_{int\ bare})}{R}-\frac{(T_{ext\ veg}-T_{int\ veg})}{R}}{\frac{(T_{ext\ bare}-T_{int\ bare})}{R}}=\frac{(T_{ext\ bare}-T_{int\ bare})-(T_{ext\ veg}-T_{int\ veg})}{(T_{ext\ bare}-T_{int\ bare})} \quad (1)$$

where Q_{bare} and Q_{veg} are the heat fluxes through the bare and vegetated exterior walls, respectively; $T_{ext\ bare}$ and $T_{ext\ veg}$ are the exterior surface temperatures of the bare and vegetated facades, respectively; $T_{int\ bare}$ and $T_{int\ veg}$ are the interior surface temperatures behind the bare and vegetated facades, respectively; and R is the thermal resistance of the facade. The wall R-values are assumed to be constant for all bare and vegetated facades, and therefore cancel out in Eq. (1). The reduction in heat flux was not calculated when exterior–interior facade surface gradient values were less than 0.5 °C because during these mild conditions, heat flux values approached zero and were not meaningful. According to this analysis, the plant layers on the opaque walls reduced heat flux by an average of 16% for the east wall, −1% for the south wall, 11% for west wall, and by 14% for the north wall when averaged over the entire measurement campaign (for an average reduction across all walls of ~10%). This difference suggests that a layer of vines can help improve the effective thermal resistance of these opaque exterior wall assemblies, especially on east and west directions. These results are similar to the findings of previous studies [1,8,10], although differences in facade orientations suggest that east and

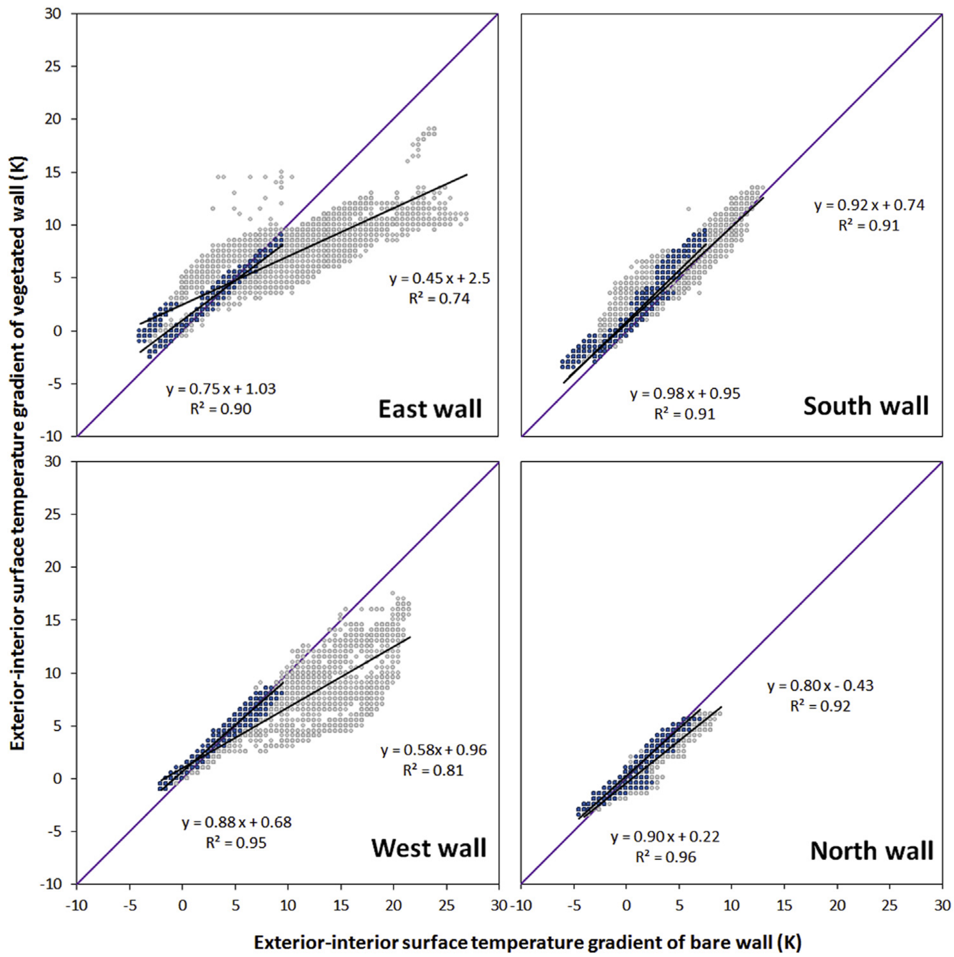

Fig. 4. Regression analysis for exterior–interior surface temperature gradient of the facades (the blue points represent a nighttime period, the gray points represent a daytime periods, and the purple line represents a 1:1 relationship). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

west wall installations of vegetation may have larger effects than south-facing installations in this particular location.

3.2. Outdoor air temperature, relative humidity, and absolute humidity near the facade

The impacts of the vegetated layer on the local microclimate are demonstrated in Figs. 5 and 6, Tables 3 and 4, which summarize the air temperature and relative humidity measured immediately adjacent to each facade, as well as the absolute humidity ratio calculated using temperature and relative humidity, and assuming conditions at sea level [17]. These measurements were made approximately 15 cm from each facade and 5 cm into each plant layer.

The observations showed that the vegetation layer also impacts the nearby microclimate conditions by decreasing the outdoor air temperature near the facades. The air temperature near the ivy-covered facades of all orientations was 0.8–2.1 °C lower than that near the bare facades, on average, depending on facade orientation. The minimum hourly difference was actually an increase of 1.0–1.5 °C behind the vegetated layers, suggesting that local air temperatures may be increased slightly during some periods when cooling by long wave radiation and/or convection is restricted. Maximum hourly reductions in immediately adjacent outdoor air temperatures of 16.6 °C were observed at the west facade and 14.1 °C at the east facade, suggesting that the air near bare walls was warmed by the exterior surface of the walls. Although these extreme values could potentially be explained by solar heating of the sensor device itself on the bare facade and shading of the sensor on the vegetated facades, similarly high temperature differences were also observed on all facades even during periods without direct solar radiation. The plant layer also reduced the hourly average of air temperature fluctuations from 18 to 53 °C near the bare facades to 19.3–45.5 °C near the vegetated facades, which contributed to the formation of more consistent microclimate conditions near the exterior walls, similar to what has been observed in other studies [1,7,8,16]. The differences in outdoor air temperatures near the plant-covered facades was statistically significant for all measured values with $p < 0.0001$.

A linear regression analysis was also performed to explore the difference in the outdoor–indoor air temperature gradients between the bare and vegetated facades for daytime and nighttime periods, as shown in Fig. 6. This outdoor–indoor temperature gradient serves as one of the key drivers of air infiltration alongside wind velocity. Predictably, the air temperature gradient near the vegetated and bare facades is similar to the surface temperature gradient and mainly is affected by solar radiation level (i.e., the difference is greater during daytime periods). The nearby air-cooling effect of plants was more pronounced when the level of solar radiation is higher.

The plant layer was also observed to alter the relative humidity (RH) near the facades. The RH near the vegetated facades of all orientations was increased by an average of 2–4% and by an hourly maximum of 18–22%. The presence of the vegetation layer also reduced the magnitude of the peak fluctuations in relative

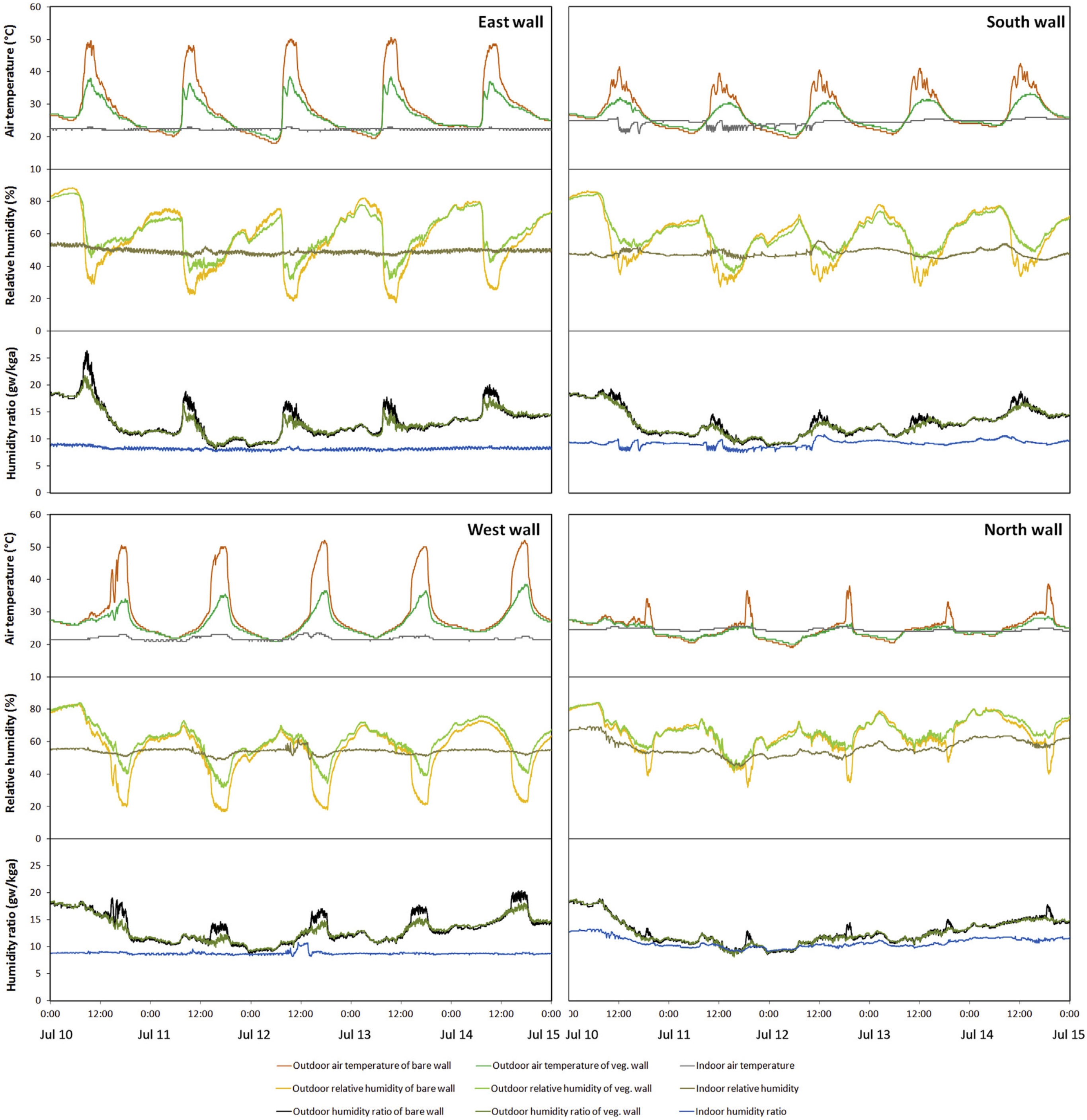

Fig. 5. Outdoor air temperature, relative humidity, and humidity ratio near the east, south, west, and north walls during July 10–15, 2013.

humidity. The hourly average of RH near the bare facades ranged from 18% to 88% (difference between minimum and maximum of 70%) while the hourly average of relative humidity near the vine-covered facades varied between 32% and 85% (difference of only 53%) during the same period. Differences in RH were statistically significant for all measured values with $p < 0.0001$.

The measured relative humidity and air temperature were also used to calculate the humidity ratio of the air near the bare and vegetated facades in order to explore the impacts of the plant layer on absolute water vapor content in the surrounding air. As shown in Fig. 5, the mean air humidity ratios near the walls within vegetation are very similar (at most 2% lower at the east wall) to those near the bare facades. Thus, although the plant layer leads to higher RH values near the walls, the impact appears to be more a function of decreasing temperature than actually altering the mass of water vapor in the air.

3.3. Air velocity near the facades

Fig. 7 and Table 5 summarize the air velocity measurements made during the length of the experiment (measured approximately 15 cm from the walls and 5 cm into the plant layer).

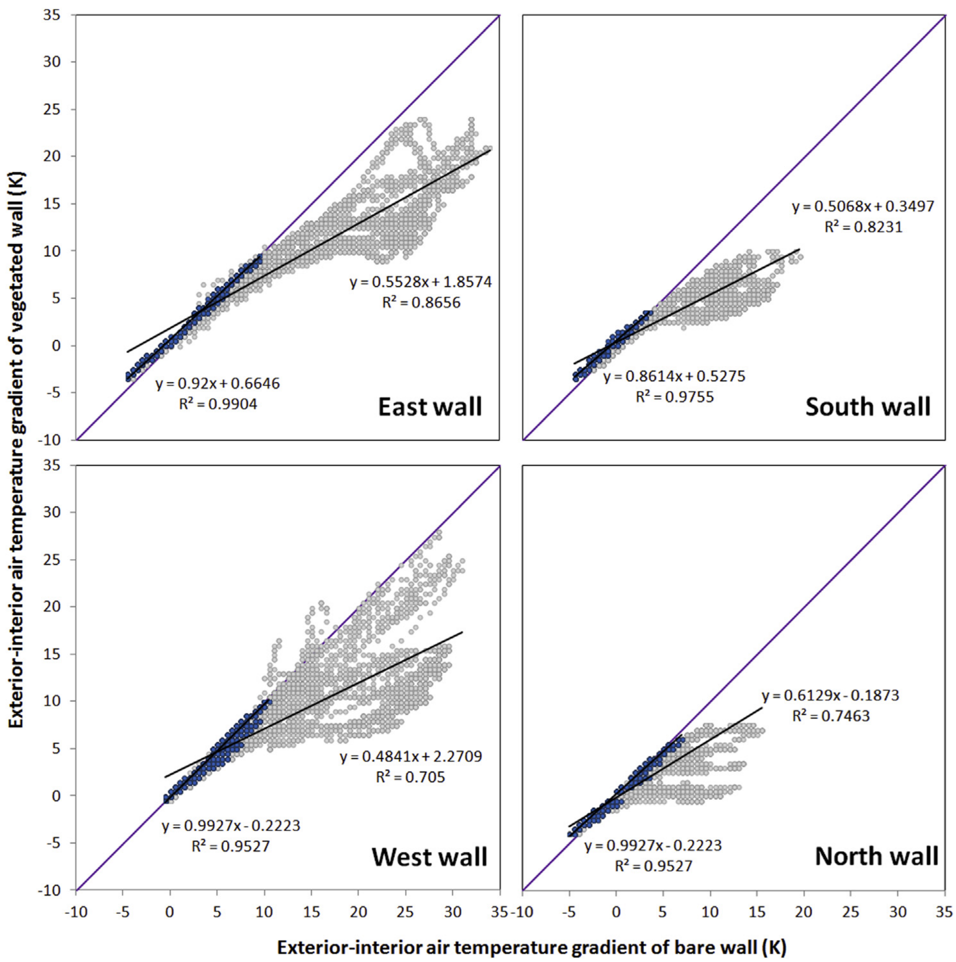

Fig. 6. Regression analysis for outdoor–indoor air temperature gradient (the blue points represent a nighttime period, the gray points represent a daytime periods, and the purple line represents a 1:1 relationship). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Air velocity near the facades varied greatly depending on orientation, vegetation coverage, and elevation. In general, the plant layer reduced adjacent air velocities, particularly for the east, south, and west exterior walls, which formed a semi-protected courtyard with relatively low wind exposure. There was no change in average wind velocities between bare and vegetated facades on the north wall, perhaps because instrumentation was installed on the second floor where higher wind speeds may have negated the impacts of the plant layer or because of interference with nearby obstructions. The average air velocity for bare facades ranged from as low as 0.26 m/s for the south wall to as high as 0.60 m/s for the north wall; conversely, the average air velocity for the vegetated facades ranged from as low as 0.15 m/s for the south wall to as high as 0.58 m/s for the north wall. These observations yield average paired reductions in air velocity near the plant-covered facades relative to the bare facades ranging from 42% to 43% on the east and west walls, respectively, to 18% on the south wall and 0% on the north wall. Differences in wind velocity were statistically significant for all measured values with $p < 0.0001$.

The relationship between the wind velocity near the bare and plant-covered facades is also shown through linear regression analysis in Fig. 8, similar to previous sections. The coefficient of determination (R^2) values for all facades are lower than similar coefficients for the surface and air temperature gradients shown in Figs. 4 and 6, meaning less straightforward and predictable

Table 3
Indoor air temperatures and outdoor air temperatures near the facades during the experiment.

	Outdoor air temperature (bare) (°C)	Outdoor air temperature (veg.) (°C)	Indoor air temperature (°C)	Reduction in outdoor air temperature (°C)
East wall, number of observations = 12,481				
Mean (±s.d.)	30.3 (±8.5)	28.4 (±5.2)	22.3 (±0.3)	1.9 (±3.9)
Hourly max.	53.0	42.7	22.9	14.1
Hourly min.	18.0	19.3	21.5	−1.3
South wall, number of observations = 8172				
Mean (±s.d.)	27.3 (±5.3)	26.2 (±3.0)	24.6 (±0.9)	1.0 (±2.7)
Hourly max.	40.7	33.0	26.0	8.6
Hourly min.	19.5	20.5	21.9	−1.2
West wall, number of observations = 12,481				
Mean (±s.d.)	30.4 (±7.5)	28.3 (±4.5)	21.9 (±0.7)	2.1 (±4.1)
Hourly max.	51.5	45.5	25.0	16.6
Hourly min.	21.0	21.0	21.1	−1.5
North wall, number of observations = 12,481				
Mean (±s.d.)	26.9 (±4.0)	26.1 (±3.0)	24.7 (±0.6)	0.8 (±1.7)
Hourly max.	37.7	33.0	26.4	8.6
Hourly min.	19.2	20.0	24.0	−1.0

Table 4
Outdoor and indoor relative humidity and humidity ratio during the experiment.

	Outdoor relative humidity (bare) (%)	Outdoor relative humidity (veg.) (%)	Indoor relative humidity (%)	Increase in outdoor relative humidity (%)	Outdoor humidity ratio (bare) (g_w/kg_a)	Outdoor humidity ratio (veg.) (g_w/kg_a)	Reduction in outdoor humidity ratio (g_w/kg_a)
East wall, number of observations = 12,481							
Mean (±s.d.)	58.4 (±18)	61.5 (±13)	50.3 (±2)	3.1 (±6)	15.0 (±3.5)	14.8 (±3.1)	0.3 (±0.9)
Hourly max.	88.0	85.0	54.1	20.9	24.6	21.5	3.8
Hourly min.	19.9	33.8	47.1	−6.3	8.6	8.7	−0.5
South wall, number of observations = 8172							
Mean (±s.d.)	60.5 (±15)	62.6 (±11)	48.2 (±2)	2.1 (±6)	13.3 (±2.7)	13.3 (±2.6)	0.1 (±0.5)
Hourly max.	86.1	84.5	56.2	17.7	18.6	18.4	1.7
Hourly min.	31.8	37.7	44.1	−4.1	8.8	9.1	−0.4
West wall, number of observations = 12,481							
Mean (±s.d.)	57.5 (±15)	61.9 (±11)	53.6 (±3)	4.4 (±1.6)	14.9 (±2.9)	14.8 (±2.8)	0.1 (±0.8)
Hourly max.	82.9	83.1	72.3	21.6	23.8	21.1	3.1
Hourly min.	17.8	32.4	48.8	−3.0	9.1	9.3	−0.8
North wall, number of observations = 12,481							
Mean (±s.d.)	65.6 (±10)	68.3 (±8)	58.3 (±5)	2.7 (±4)	14.5 (±3.0)	14.5 (±2.9)	0.0 (±0.4)
Hourly max.	84.5	85.1	68.7	18.2	20.1	19.2	1.4
Hourly min.	39.2	45.9	45.4	−2.5	8.9	8.9	−0.6

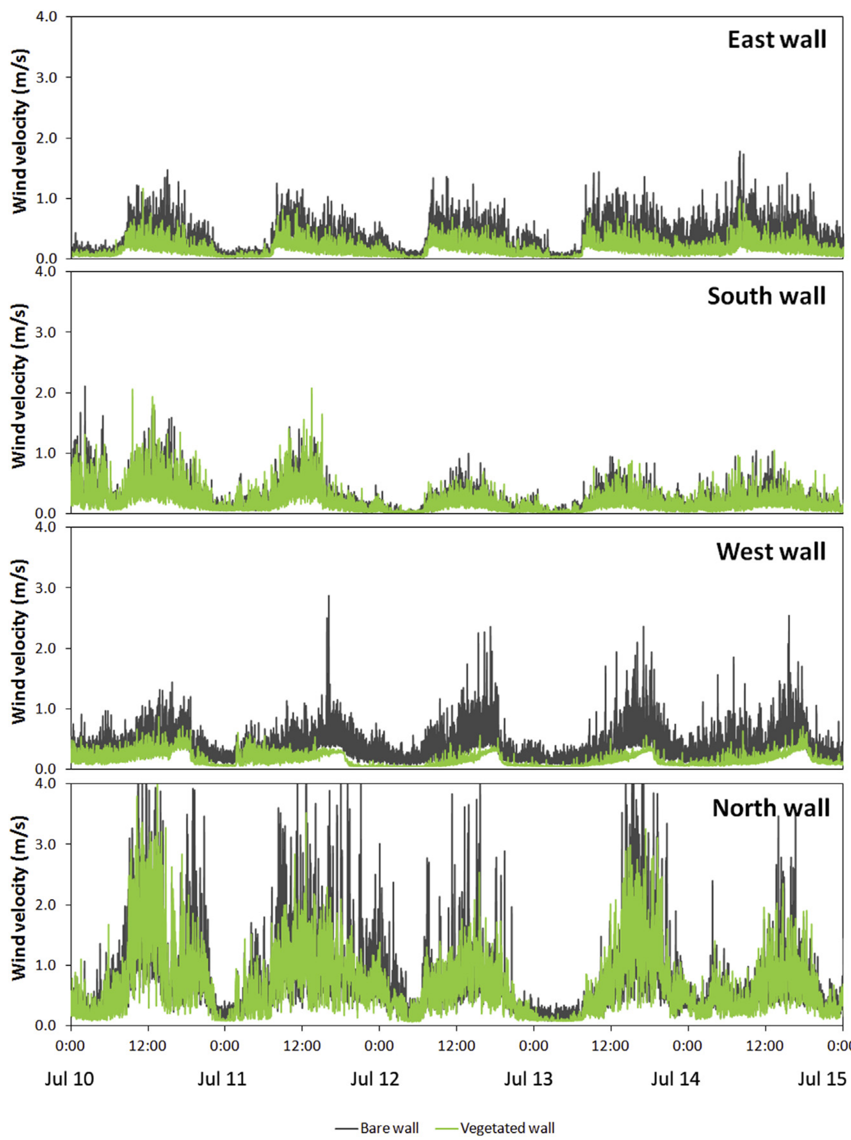

Fig. 7. Air velocity near the east, south, west, and north walls during July 10–14, 2013.

Table 5
Air velocity near the facades during the experiment.

	Air velocity							
	East wall		South wall		West wall		North wall	
	Bare	Veg.	Bare	Veg.	Bare	Veg.	Bare	Veg.
Number of observations = 10,554								
Mean (m/s)	0.29	0.15	0.26	0.21	0.4	0.21	0.60	0.58
(±s.d.) (m/s)	(±0.2)	(±0.1)	(±0.2)	(±0.2)	(±0.3)	(±0.2)	(±0.5)	(±0.5)
Hourly max. (m/s)	0.6	0.34	0.78	0.62	0.72	0.82	1.76	1.95
Hourly min. (m/s)	0.05	0.03	0.03	0.03	0.14	0.05	0.15	0.08
Mean reduction (m/s)		0.14		0.05		0.19		0.02
Hourly max. reduction (m/s)		0.31		0.27		0.49		0.24
Mean reduction (%)		42%		18%		43%		0%
Hourly max. reduction (%)		55%		46%		83%		51%

relationships. The time of the day also had very little effect on wind velocity reductions near the plant-covered walls, contrary to surface and air temperature gradients. However, these experimental data confirm the impact of facade vegetation on reducing wind speed described in previous studies [10,18–20]. These results suggest that a plant layer could potentially lead to reduced convective heat transfer on the surface as has been mentioned in previous studies, as well as reduced air infiltration in buildings by limiting the driving forces of infiltration (which is explored in the following section).

3.4. *Modeling the impact of vegetated facades on air infiltration rates*

Finally, the experimental air velocity and outdoor–indoor air temperature gradient data were used to predict the likely impact of vegetation on air infiltration rates through the four measured facades. The LBL Leakage Model was used to predict air infiltration rates normalized by wall area for each measured facade (both bare and vegetated) under the measured conditions of indoor–outdoor temperature differences and wind velocities during the

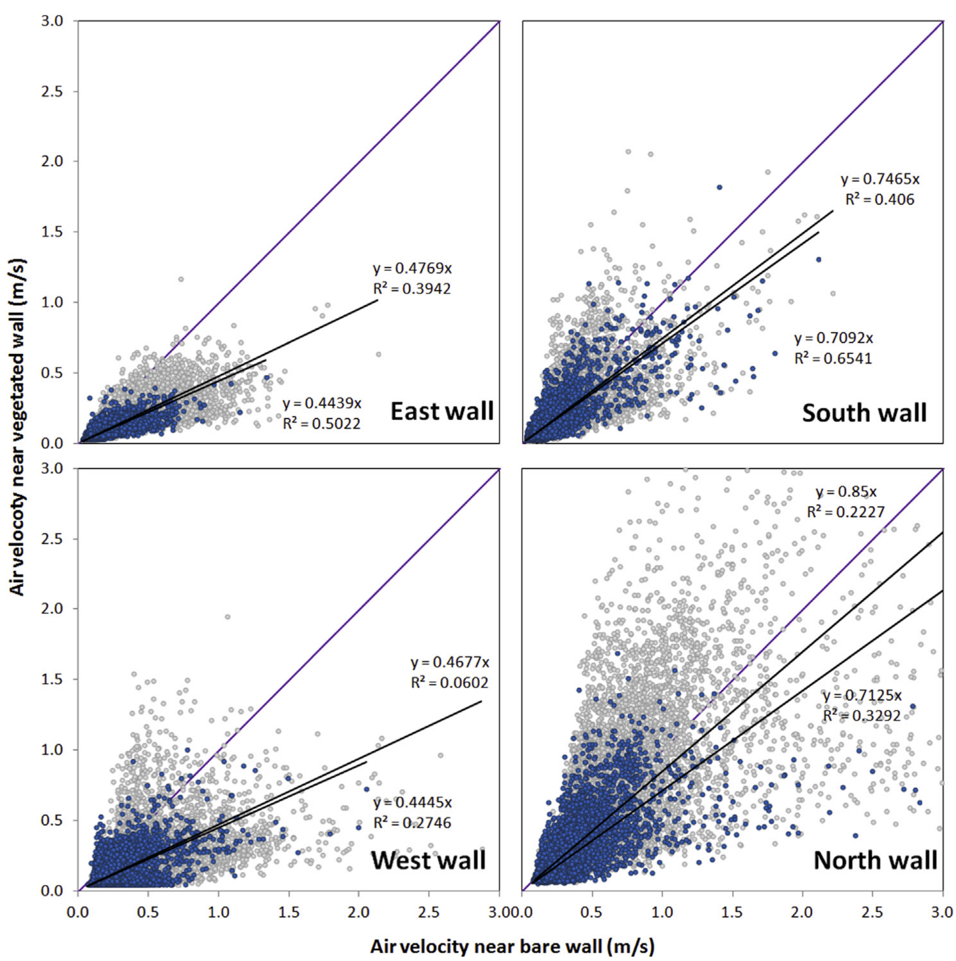

Fig. 8. Regression analysis for air velocity near the vegetated versus bare facades (the blue points represent a nighttime period, the gray points represent a daytime periods, and the purple line represents a 1:1 relationship). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

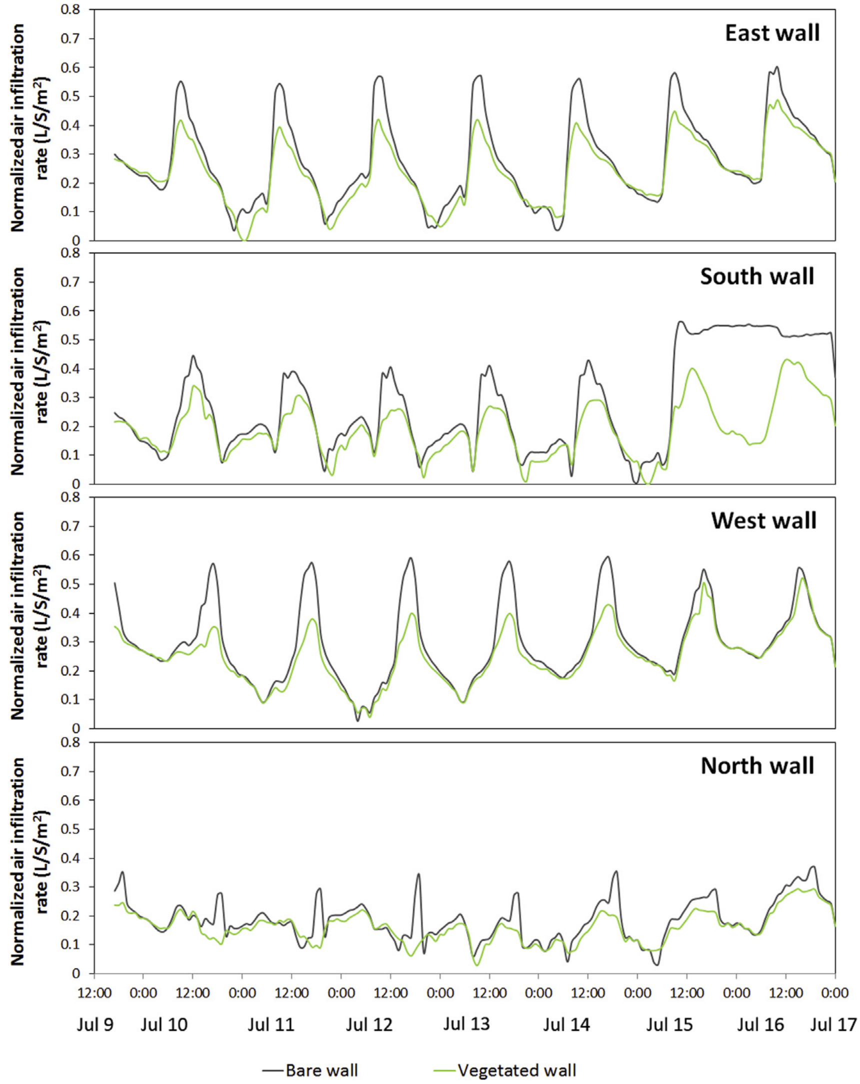

Fig. 9. Hourly normalized air infiltration rate through 1 m^2 of each wall during the 6 days of the field experiment.

experimental campaign. The measured buildings' walls were assumed to have the airtightness typical for commercial buildings (we were not able to measure airtightness). The LBL Leakage model [22–24] estimates the infiltration airflow rate through cracks and gaps in the building envelope, Q_{inf} (L/s), as:

$$Q_{inf} = A_{inf}\sqrt{k_s|T_{in} - T_{out}| + k_w U^2} \quad (2)$$

where A_{inf} is the effective air leakage area of the wall (cm^2), k_s is a stack coefficient ($(L/s)^2/(cm^4\ K)$), k_w is a wind coefficient ($(L/s)^2/(cm^4(m/s)^2)$), T_{in} and T_{out} are the indoor and outdoor temperatures (K), and U is the wind speed (m/s). As A_{inf} was not known for the test case buildings, the air infiltration rate was estimated first normalized for 1 cm^2 of leakage area (i.e., Q_{inf}/A_{inf}). Then, to make the model results more generalizable to other facades, it was assumed that each facade had an effective floor-normalized leakage area (A_L) that is typical for conventional buildings ($A_L = 5.27$ cm^2/m^2 at a reference pressure difference of 4 Pa) [25]. These assumptions allowed estimating the air infiltration rate normalized for a 1 m^2 section of wall area, A_{norm} ($(L/s)/m^2$), using the following equation:

$$A_{norm} = \frac{Q_{inf}}{A_{inf}} \times A_L \quad (3)$$

The value of this approach is that it can provide estimates of the impact of vegetation on air infiltration rates through opaque walls with typical cracks and gaps, regardless of the impact of other components, such as the area of windows and doors on the facades. If the amount of wall area covered with vegetation is known, air infiltration flow rates can be estimated by multiplying by wall area, and overall air exchange rates due to infiltration alone can be estimated by dividing by the indoor volume.

A stack coefficient, k_s, was assumed to be 0.000435 $[(L/s)^2/(cm^4\ K)]$ (appropriate for three-story buildings) and a wind coefficient, k_w, was assumed to be 0.000271 $[(L/s)^2/(cm^4(m/s)^2)]$ [24], also for three-story buildings with the shelter class 3 (assuming typical shelter caused by other buildings across the street from the buildings in this work) [17]. Hourly averages of air velocity and indoor–outdoor air temperature gradients for each wall during the 6 days of the experiment were then used to estimate the hourly normalized air infiltration rate through 1 m^2 of each bare and vegetated wall, as shown in Fig. 9.

Reductions in outdoor air velocity and adjacent outdoor air temperature near the vegetated facades resulted in predictions of hourly normalized air infiltration rates at each facade that were typically lower than the estimates for the bare facades, particularly during daytime periods. Average reductions in hourly estimates of normalized air infiltration rates on the vegetated facades were 0.04, 0.04, 0.05, and 0.02 (L/s)/m^2 for the east, south, west, and north walls, respectively, compared to predicted air infiltration rates on the same bare facades of 0.25, 0.20, 0.28, and 0.17 (L/s)/m^2. These differences correspond to mean relative reductions in air infiltration rates through the vegetated facades of approximately 8%, 4%, 12%, and 8% for each orientation under the measured conditions. Maximum reductions in hourly estimates of normalized air infiltration rates on the vegetated facades were as high as 97%, 96%, 42%, and 71% for the east, south, west, and north walls, respectively. These results suggest that vegetation, when applied over these four opaque facades and subjected to the external conditions described herein, could possibly reduce air infiltration rates through walls by as much as 4–12%, on average, which could serve as another, previously unexplored, mechanism by which vegetated walls can reduce energy consumption in buildings. Importantly, the percentage reductions of these predictions were not sensitive to assumptions for airtightness of opaque walls (although absolute values scale linearly with assumptions for facade airtightness). However, these results suggest that more experiments should be conducted in other facilities to explore the effects of vegetated walls on actual air infiltration rates using standardized methods of tracer gas testing.

4. Conclusion

An experiment measuring the effects of climbing plants on facade thermal performance and local microclimate was conducted for several days in July 2013 on university buildings in Chicago, IL. The experiment involved measurements of facade surface temperature, air temperature, relative humidity, absolute humidity, and air velocity near the four facades of different orientations in the existing buildings. The experimental data and analyzed results are summarized as follows:

- A layer of climbing plants caused a reduction in the facade exterior surface temperatures: 0.7 °C lower on average, reaching a maximum hourly reduction of 12.6 °C on the east facade. The highest surface temperature reduction was measured on the east and west facades exposed to high intensity solar radiation in early morning and late evening hours at the low sun angles.
- Heat flux through the opaque exterior walls was estimated to be reduced by an average of 10% by the plant layers across all of the four facades, with the largest impacts occurring during daytime periods.
- The vegetation layer created a generally milder local microclimate near the facades as the outdoor air temperature near the vegetated facade was on average 0.8–2.1 °C lower (depending on orientation) and the relative humidity was 2–4% higher than that near the bare facades. However, although the plant layer created higher relative humidity near the walls, the absolute humidity ratio was actually similar for both bare and vegetated facades.
- Average air velocity near the vegetated facades was as much as 42–43% lower than the bare facades on the east and west walls, respectively, but as little as 18% lower on the south wall and there was no change on the north wall (perhaps because of larger wind velocities at this higher elevation or because of nearby obstructions).
- The combined effects of reduced outdoor air velocity and temperatures near vegetated facades were predicted to reduce air infiltration rates in the measured buildings (normalized per unit wall area) by approximately 8%, 4%, 12%, and 8% (for the east, south, west, and north walls) on average under the measured conditions.

Acknowledgments

This research was conducted as part of the major capital renewal project for the complex of campus buildings at the University of Chicago. The project was funded by the University of Chicago Facilities Services.

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