# COOLING EFFECT OF IVY ON A WALL

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***Green plants affect the temperature and moisture of the microclimate in the surrounding area. The heat flux distribution on a west-facing wall of a two-story building covered with thick ivy was measured experimentally to investigate the cooling effect of the ivy. The shading due to the ivy can effectively reduce the radiation gain of the building in summer. The heat transfer mechanisms were also analyzed theoretically to determine the basis for the cooling effect of the green wall. The green wall reduced the peak-cooling load transferred through the west-facing wall by 28% on a clear summer day.***

Many factors may affect the indoor environment, such as indoor and outdoor heat and moisture sources, the thermal design of the structure, the effect of other buildings, the green ratio, etc. Building designs have depended on air conditioning systems for a long time to supply a comfortable temperature and humidity environment, but now we realize that air conditioning is not the best solution. Energy is used, the environment degrades, and perhaps most important, the "sick building syndrome" develops, probably as a result of the air-conditioning system. With a wider knowledge of earth sustainability, more people desire a better way to have a satisfactory environment using less high-level energy and making the most of renewable resources. People desire energy conservation and environmental protection. People have long known the great cooling effect of an ivy-covered wall in the summer. Studies have shown that buildings with proper landscaping have lower temperatures than ordinary buildings in the summer [1–3]. In addition, thick vines or ivies can increase the air moisture content by 10–20% [4]. Urban landscaping can beautify the scenery, improve the environmental quality, decrease pollution, and reduce dust and noise. The benefits of landscaping have been widely recognized by architects, urban planners, and administrators. There have been many field studies, but most have provided only qualitative results and lacked thorough quantitative analysis. This article describes a two-summer experiment on a two-story building investigating the temperature-reduction process on a green wall, the energy transfer between the plants and the wall, and the theoretical principles for the cooling effect.

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## NOMENCLATURE

| | |
|---|---|
| Bi | Biot number |
| $c$ | thermal capacity of the wall, 0.88 kJ/kg K [6] |
| $d$ | characteristic dimension along the wind direction, m |
| Fo | Fourier number |
| $h_{bw}$ | convective heat transfer coefficient on the bare wall, W/m$^2$ K |
| $h_f$ | convective heat transfer coefficient on the inside surface of the wall, 8.7 W/m$^2$ K [7] |
| $h_{fg}$ | water latent heat, J/kg |
| $h_l$ | convective heat transfer coefficient on the leaves, W/m$^2$ K |
| $h_w$ | convective heat transfer coefficient on the green wall, W/m$^2$ K |
| $\dot{m}$ | evaporation rate, kg/s m$^2$ |
| $N$ | node number |
| $q_{bw}$ | net heat flux to the bare wall, W/m$^2$ |
| $q_{bwe}$ | radiative heat flux between the bare wall and the environment, W/m$^2$ |
| $q_{i,t}$ | heat flux at time $t$ at the inner surface of the wall, W/m$^2$ |
| $q_{le}$ | radiative heat flux between the leaves and the environment other than the wall, W/m$^2$ |
| $q_{lw}$ | radiative heat flux between the leaves and the wall, W/m$^2$ |
| $q_{rad}$ | horizontal solar radiation flux, W/m$^2$ |
| $q_w$ | net heat flux to the green wall, W/m$^2$ |
| $T_{bw}$ | bare wall temperature, K |
| $T_f$ | indoor temperature, K |
| $T_l$ | leaf temperature, K |
| $T_w$ | wall temperature, K |
| $T_\infty$ | outdoor temperature, K |
| $v$ | wind speed, m/s |
| $x$ | ratio of the area covered by green leaves to the total wall area |
| $\alpha_l$ | leaf absorptivity, 0.75 [5] |
| $\alpha_w$ | wall absorptivity, 0.7 [6] |
| $\varepsilon_l$ | leaf emissivity, 0.95 [5] |
| $\varepsilon_w$ | wall emissivity, 0.9 [6] |
| $\lambda$ | wall thermal conductivity, 0.81 W/m K [6] |
| $\rho$ | density of the wall, 1,800 kg/m$^3$ |
| $\sigma$ | Boltzmann constant, $5.675 \times 10^{-8}$ W/m$^2$ K$^4$ |
| $\tau_l$ | leaf transmissivity, 0.15 [5] |
| $\Delta\tau$ | time interval, s |
| $\Delta x$ | distance between two nodes, m |

## EXPERIMENTAL DESCRIPTION

### Objective

For ivy-covered walls, some solar radiation is reflected by the leaves and some penetrates the leaf layer and is absorbed by the wall, while the rest is absorbed by the green leaves. Of the solar energy absorbed by the leaf layer, some is used for photosynthesis, some for transpiration cooling, some is emitted as long-wave radiation, and the rest is given off by heat transfer to the surrounding air. These energy transfers must be known to determine how much the green plants can lower the heat gain during the day. At night, when the atmospheric temperature is relatively low, buildings generally cool by losing energy by long-wave radiation. However, a leaf layer existing between the wall and the atmosphere would reduce the long-wave radiation and the heat discharge. Therefore, the effects of both day and night heat transfer processes must be considered to evaluate the effect of the green wall on the indoor environment. The aim of this experiment is to gather data as a basis for quantitative analysis.

### Site

A suitable building should have the following characteristics:

- A thick leaf layer covering the outer wall
- A relatively steady thermal load
- No shading other than the ivy

The Tsinghua University Library, Beijing, was chosen for the experiment, as shown in Figure 1. The older part of the library is a two-story building, built in 1919, with heavy brick outer walls, and a tiled peaked roof. The building is in a good green area, has west-facing and south-facing walls covered with thick ivy, has bushes 1 m high around the whole building, and has a gingko grove by the south part of the west-facing wall. The measurement points are on the north part of the west-facing wall on the second floor. The room inside the building at that point is a large reading room 50 m long in the north–south direction, 15 m wide in the east–west direction, and 6 m high. Relatively few people use the room, and the temperature varies little during the day and night. The wall gets sun from 11:30 a.m. to 6:00 p.m. The ivy is very thick on the west-facing wall in the summer, with a green leaf layer standing about 10 cm away from the wall, and dense twigs under the leaf layer.

## INSTRUMENTS AND SETUP

### Solar Radiation

A DFY-2 type pyranometer was mounted facing horizontally on the west-facing wall to measure the solar radiation. The data were recorded automatically

**Figure 1.** West-facing view of Tsinghua University Library (old part).

for a month at 5-min intervals. The pyranometer was calibrated by the Chinese National Weather Bureau.

### Temperature

The temperatures were measured at five points, all the same height. The points were on the surface of the wall, 5 cm away from the wall, on the leaf, 5 cm from the leaf, and 10 cm from the leaf. The leaf and wall temperatures were measured by 0.2-mm-diameter copper-constantan thermocouples. To reduce the influence of the surrounding air and solar radiation, the tip was inserted into the leaf. The air temperature was measured automatically by RHLOG intelligent thermometers developed by Tsinghua Tongfang Company (Beijing). The indoor temperature was also measured. The measurement interval was 10 min. A DHM2 type hygrometer measured the relative humidity.

### Heat Flux

A heat flux meter was attached to the wall with oil having the same surface color as the wall. The heat flux was recorded automatically every 5 min for a month. Error rate was less than 4%.

### Wind Velocity

A two-direction anemometer was used to measure the wind speed over the leaf layer.

A bare wall exposed directly to the sun was used as control. The bare wall was obtained by cutting away a square meter of leaves and stems at the same height and on the same wall with a similar measurement system. The surface temperature, the heat flux, and the air temperature 5 cm away from the wall were then recorded.

The apparatus used in the measurement are sketched in Figure 2.

The experiment was repeated at the same site for two summers, 1996 and 1997. The uncertainty of the experiment was not considered in this article.

## COMPUTATIONAL EQUATIONS

There were three fundamental equations in this situation. The equations for the ivy layer, ivy wall, and bare wall were written out. The input data in the equations were obtained from the measurement. The solar radiation, the temperatures, and the heat fluxes were the known quantities in the equations. The unknowns were the transpiration rate from the leaves and the convective heat transfer coefficient at the two types of walls. These equations could then be used to calculate the energy transfers in the system. The convective heat transfer coefficient at the two types of the walls could enhance our understanding of cooling effect of the ivy.

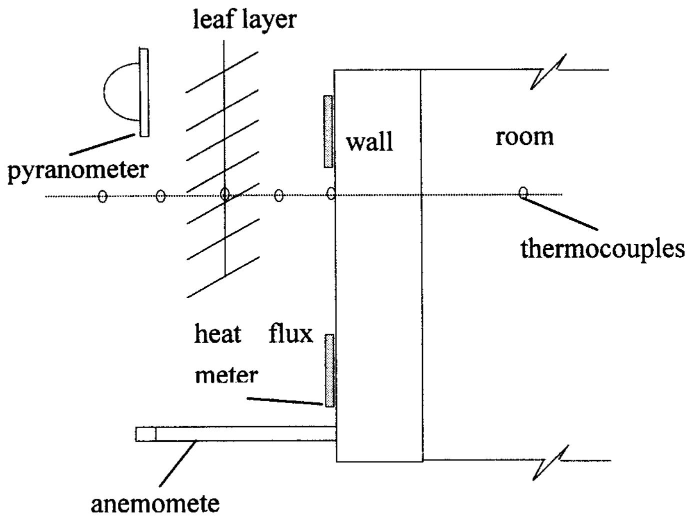


**Figure 2.** Experimental setup.

The theoretical model of the heat transfer to the leaves and to the wall assumed:

- No overlap of the leaf layers
- Uniform leaf temperature
- The ivy had negligible thermal capacity

The energy balance for the leaf layer was

$$x\alpha_l q_{\mathrm{rad}} - 2h_l(T_l - T_\alpha) - q_{le} - q_{lw} - h_{fg}\dot{m} = 0 \tag{1}$$

The ratio of the area covered by green leaves to the total wall area, $x$, was determined to be 0.95 based on pictures of the ivy-covered wall.

The energy balance for the ivy-covered wall was

$$(1 - x)\alpha_w q_{\mathrm{rad}} + \tau_l q_{\mathrm{rad}} + q_{lw} - h_w(T_w - T_\alpha) - q_w = 0 \tag{2}$$

The energy balance for the bare wall was

$$\alpha_w q_{\mathrm{rad}} - q_{\mathrm{bwe}} - h_{\mathrm{bw}}(T_{\mathrm{bw}} - T_\alpha) - q_{\mathrm{bw}} = 0 \tag{3}$$

The convective heat transfer coefficient $h_l$ in Eq. (1) was calculated using the semiexperimental formula [5]

$$h_l = 9.14 * \sqrt{\frac{v}{d}} \tag{4}$$

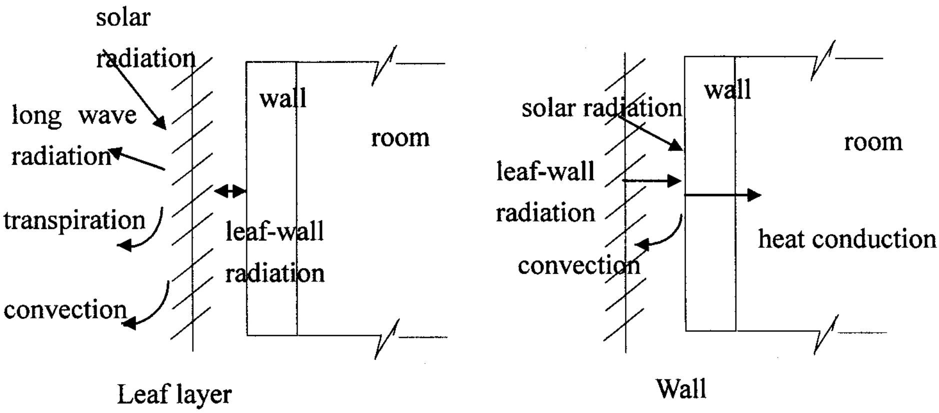


**Figure 3.** Heat flux mechanics.

The radiant heat flux between the leaves and the wall, $q_{lw}$, in Eq. (1) was calculated by the equation:

$$q_{lw} = \sigma(T_l^4 - T_w^4) \Big/ \left(\frac{1}{\varepsilon_l} + \frac{1}{\varepsilon_w} - 1\right) \tag{5}$$

The radiant heat flux between the leaves and the environment other than the wall, $q_{le}$ in Eq. (1), and the radiant heat flux between the bare wall and the environment, $q_{\mathrm{bwe}}$ in Eq. (3), were neglected in the day-time calculation.

From the ivy layer energy equation (1) and equation (5), the long-wave radiation between the leave layer and the ivy wall, the latent heat, and convective heat transfer from the leave layer could be calculated. From the ivy wall energy equation (2), the convective heat transfer from the ivy wall was calculated to compare with the convective heat transfer from the bare wall, which could be calculated from the bare wall equation (3).

To compare the heat conducted through the two types of walls, an explicit finite-difference method was used to evaluate the hour-by-hour heat flux at the inside surface of the wall. This calculation shows the final load saving of the ivy on the building.

The temperature of the wall at node $i$ and time $k+1$ was expressed as

$$T_i^{k+1} = \mathrm{Fo}(T_{i-1}^k + T_{i+1}^k) + (1 - 2\,\mathrm{Fo})T_i^k \tag{6}$$

Because the heat flux on the outside surface of the wall and the temperature in the room were known, the temperature at the two surfaces of the wall could be expressed as

$$T_1^{k+1} = 2\,\mathrm{Fo}\,T_2^k + (1 - 2\,\mathrm{Fo})T_1^k + (2\,\mathrm{Fo}\,\Delta x/\lambda)q^k \tag{7}$$

$$T_{N+1}^{k+1} = 2\,\mathrm{Fo}\left(T_N^k + \mathrm{Bi}\,T_f^k\right) + (1 - 2\,\mathrm{Fo} - 2\,\mathrm{Bi}\,\mathrm{Fo})T_{N+1}^k \tag{8}$$

In Eqs. (6–8), The Fourier number and the Biot number were defined as

$$\text{Fo} = \lambda \Delta \tau / \rho c \, \Delta x^2 \tag{9}$$

$$\text{Bi} = \frac{h_f \, \Delta x}{\lambda} \tag{10}$$

The convective heat transfer coefficient on the inside surface of the solid masonry wall was 8.7 $W/m^2$ K, assuming still air in the room, as specified in the *Chinese Air Conditioning Design Handbook* [7]. The time interval was 300 s. Distance between nodes was 0.037 m, so there was a total of 10 nodes across the wall. The initial wall temperature was assumed to be uniform 20°C. Calculation was continued until the temperature distribution across the wall did not change from day to day.

## RESULTS AND ANALYSIS

Data for the energy analysis were recorded in good weather. June 9, 1997, was a clear day with little wind, and the relative humidity was around 43%. Figures 4 and 5 are the measured data. Figures 6, 7, and 8 are the energy transfer analysis of the leaf layer, the ivy wall, and the bare wall. Figure 9 is the heat flux to the outside of the two types of walls, which was the input data in the heat gain calculation. Figure 10 is the calculated heat gain on the inner side of the two types of walls.

Figure 4 shows the measured average and maximum temperature distribution of the measured points. Figure 5 shows the variation of the green wall and the bare wall temperatures during the day. The data in Figures 4 and 5 show that the average temperature of the leaf was 8.2°C higher than the average temperature of

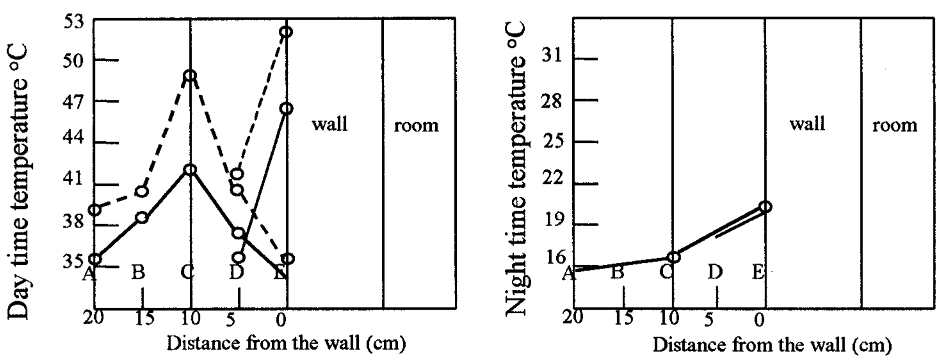


**Figure 4.** Temperature distribution on June 9, 1996. In the left figure, the solid line represents the average temperature from 14:20 p.m. to 6:25 p.m., which is during daylight. The dashed line represents the maximum temperature at 4:40 p.m. The lines with only two points show the parallel situation, on the bare wall. On the right figure, the solid line represents the average temperature from 9:25 p.m. to the next morning at 4:15 a.m. Since the temperature is steady at night, the maximum values are not shown. The short line shows the parallel situation on the bare wall.

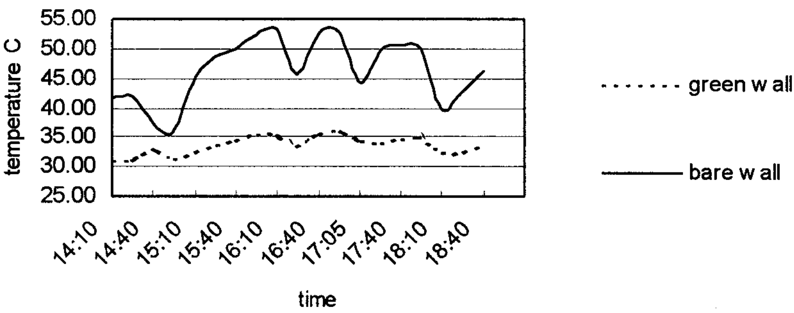


**Figure 5.** Surface temperature comparison on June 9, 1996.

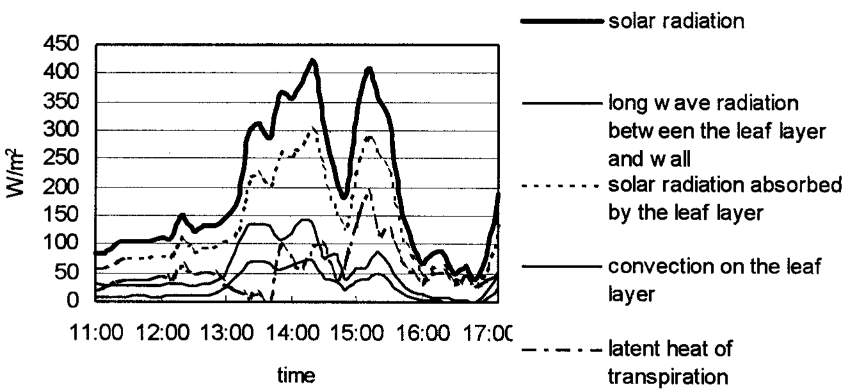


**Figure 6.** Energy transfer to the leaf layer on July 24, 1996.

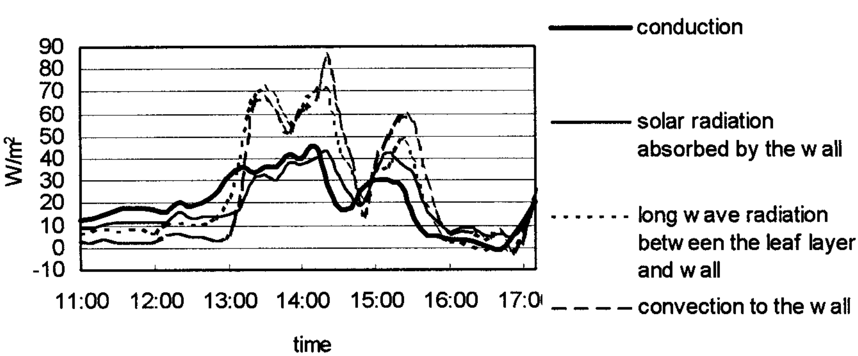


**Figure 7.** Energy transfer to the green wall on July 24, 1996.

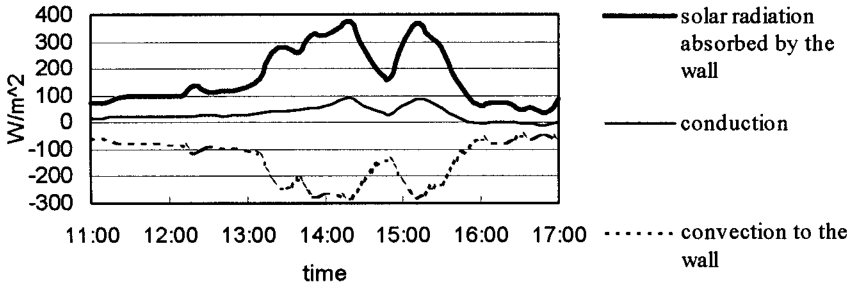


**Figure 8.** Energy transfer to the bare wall on July 24, 1996.

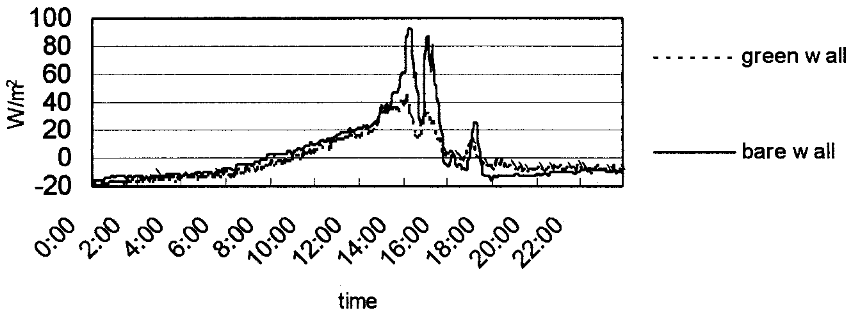


**Figure 9.** Average heat flux to both types of walls on July 24, 1996.

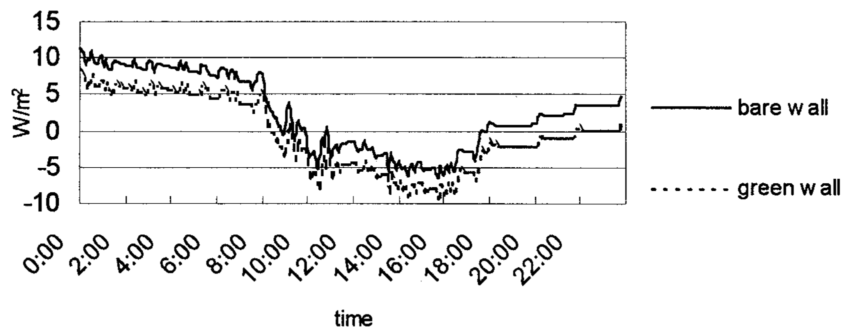


**Figure 10.** Calculated conductive heat flux to the inside surfaces of both types of walls on July 24, 1996.

the wall under the leaves when the sun was shining. Even though the absorptivity of the leaves was similar to that of the wall, the average temperature of the leaves was 4.5°C lower than the temperature of the bare wall exposed directly to the sun when the sun was shining. Most of the solar radiation received by the bare wall was absorbed by the wall, causing the wall temperature to rise. For the leaf layer, the evaporation and the thermal convection on both sides reduced the temperature of the leaves, causing the temperature of the leaves to be lower than that of the exposed wall.

At night, the temperatures of the green wall were slightly warmer than those of the bare wall. The thermal convection was similar on the two walls, but long-wave radiation from the bare wall caused it to cool more. As shown in Figure 4, the night-time leaf temperature was 16°C and the night-time bare wall temperature was 20°C. Since the air temperature was very low, the radiation from the covered wall to the leaf layer was less than the radiation from the bare wall to the air.

The energy fluxes to the wall and the leaf layer on July 24, 1996, were analyzed in detail (Figure 6). Since the transpiration curve in Figure 6 was parallel to the radiation curve, the energy absorbed by the latent heat was related directly to the solar radiation. The average transpiration heat flux was 56.8 $W/m^2$, which was 42.5% of the solar radiation absorbed by the leaves. Another 40% of the solar radiation absorbed by the leaves was lost by thermal convection, and 18.9% was lost by long-wave radiation to the wall. Figure 7 shows that the west-facing ivy-covered wall received an average 186 $W/m^2$ of solar radiation during the day. The solar radiation reflected by the green leaves was 27.9 $W/m^2$, that absorbed by the leaves was 133 $W/m^2$, and that passing through the leaf layer was 28 $W/m^2$. The covered wall absorbed 20 $W/m^2$ of solar radiation and 25 $W/m^2$ of long-wave radiation, and released 25 $W/m^2$ by convection. Here 20 $W/m^2$ flowed into the room.

Figure 9 shows the heat flux to the ivy-covered wall compared with that of the bare wall on July 24, 1996. The heat flux to the green wall was one-half that of the bare wall when the sun was shining, which would substantially reduce the air-conditioning peak load in the summer. At night the heat flux from the bare wall was slightly higher than that from the green surface, mainly due to the difference in the long-wave radiation from the two types of walls.

Data for July 24, 1996, was selected to calculate the heat flux at the inside surface of the wall. The results are shown in Figure 10. The average conductive heat flux through the bare wall was greater than the conduction through the green wall. The average bare-wall conductive heat flux was 2.045 $W/m^2$, while the average green-wall heat flux was nearly zero. The maximum heat flux from the bare wall was 11.38 $W/m^2$, while the maximum heat flux from the green wall was 8.16 $W/m^2$. Therefore the peak-cooling load of the building was reduced by 28%. The calculation also showed that the peak heat flux through the wall was delayed by about 8 h.

The convective heat transfer coefficient on the green wall averaged 10.60 $W/m^2 K$ on July 24, 1996, which was appropriate for natural convection. The convective heat transfer coefficient on the bare wall averaged 33.25 $W/m^2 K$, which was larger than on the green wall, because there were no leaves to stop the wind and reduce the rising air current along the wall.

## CONCLUSIONS

The cooling effect of green ivy on a building wall was investigated by simultaneously measuring the wall temperature for both a bare wall and an ivy-covered wall during both the day and the night. The green plants reduce the peak-cooling load transferred through the west-facing wall by 28% on a clear summer day. Because the west-facing wall receives more heat than other surfaces in summer, the air-conditioning load would be reduced and the peak load would be reduced substantially by the green ivy. The green wall reduces the heat gain by absorbing and reflecting the solar radiation. Forty percent of the energy absorbed by the leaves is lost by convection, 42% by transpiration, and the rest by long-wave radiation to the environment.

At night, the building releases heat by long-wave radiation to the sky and by convection with the surrounding air. When the leaf temperature is equal to the air temperature, the transpiration is close to zero and the leaf layer reduces the heat loss from the building because it reduces the radiation heat transfer. Therefore, the bare wall temperature was slightly *lower* than the green wall temperature at night. If other measures such as nocturnal ventilation were used to cool the building, this negative effect would be diminished.

The cooling effect of green ivy varies with the season. In July and the beginning of August, the green ivy substantially reduces the energy absorbed by the wall and decreases the indoor temperature. In June the outdoor temperature is relatively low and the thermal load of the building is also very low, so a building covered with green ivy may have relatively higher indoor temperatures than a building without green ivy.

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