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Impact of plants occultation on energy balance: Experimental study

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Abstract

This paper presents the results of the validation of an experimental method for studying the thermal benefits of green façades. The main aim is to evaluate the impact of plants occultation on energy performance of a vertical wall in the temperate climate of the city of Lille in northern France. An experimental platform consisting of three identical prototypes (three boxes as thermal labs) has been designed and instrumented. Each prototype has been highly insulated from each faces except from the vertical southern wall which was realized with a poor thermal conductivity material. The following measurements were taken: ambient temperature (outside and inside thermal labs), external and internal surface temperatures of southern walls, heat fluxes transferred through south verticals walls (reference and vegetalized walls), solar incident radiation and wind velocity variation under instantaneous real climatic conditions. This enabled the analysis of the variation of energy balance according to the presence or not of a shading effect on the south vertical walls as well as their coverage rate. Several tests were performed on the three experimental thermal labs by imposing a leaf coverage rate which differs during each measurement. The results have shown that masking reduces the outside temperature and enhances the interior thermal comfort especially during summer.

Key words: Vegetalized walls, energy performance, buildings envelopes, shading effect, leaf coverage rate, heat transfers.

26 **Nomenclature**

Symbols:		λ	thermal conductivity, $W.m^{-2}.K^{-1}$
T	temperature, K	Indices / Exponents	
VW	vegetalized wall	AG	air gap
GW	extensive green wall	cc	cellular concrete
LW	living wall	ext	external
OM	occulted meshes	int	internal
I_s^\downarrow	incident solar radiation, W/m^2	occ	occultation
SWR	short-wave radiation, W/m^2	Sol	solar
LWR	long wave radiation, W/m^2	So	outside surface
Greek letters:		Si	inside surface
ϕ	flux density, W/m^2	vw	vegetalized wall

27 **1. Introduction**

28 The vegetalization has been associated to buildings since the earliest constructions and the hanging gardens of
 29 Babylon could be considered as the first example (sixth century BC) [1]. The elites of the Roman civilization had
 30 also used to grow vines on their balconies and vegetalized walls were previously integrated into their mausoleums
 31 [2]. In the form we know today, the idea of green walls has made its way from the 70s in Germany [3] to contract
 32 principally the phenomenon of urban heat island which results in a temperature difference between a rural and an
 33 urban area of the same region [4,5]. This is mainly due to the human activities, transportation, energy consumption
 34 and heat losses of buildings. The temperature increase in urban centres was defined as a direct result of substitution
 35 of natural surfaces by impermeablized concrete and asphalt surfaces absorbing more solar radiation (very low
 36 albedo) without evapotranspiration. In other words, the solar radiation will be trapped through a reduction in
 37 reflecting surface areas and the presence of pollutants (CO_2 , particles, aerosols, etc...) in the urban atmosphere
 38 hence the temperature increases in an urban area compared to rural areas [6–14].

39 In order to handle this phenomenon, the new initiatives and strategies of urban development try to increase the
 40 ratio of parks, gardens and vegetation surfaces in retrofit and improvement of towns. However, this wouldn't be
 41 really possible in mega-cities such as Tokyo, New York, Berlin or Paris, where the tendency is to optimize every
 42 available space in favour of new constructions and hence allowing better organization of space and important
 43 economy for transport networks. Therefore, the best solution for mega-cities is the vegetalization of building
 44 envelopes that will retrieve every square meter of natural earth removed from the ground by an equivalent natural

45 soil on roofs. Natural surfaces in a city might even strengthen through the vegetalization of vertical walls of new
46 and existing buildings given that walls offer greater potential in terms of reception areas, and disposal facilities for
47 plant species compared with roofs.

48 The reasons for which new urban development strategies encourage more use of green roofs and vertical green
49 walls also remains in their ability to improve the thermal resistance of the building envelope in summer for hot
50 climate regions and during winter for cold climate regions that do not have long periods of frost and severe winters
51 [3]. The improvement of the thermal resistance of building envelope in winter is mainly due to the reduction of
52 wind velocity at the outer surface (superficial heat exchange coefficient) as the wind flow is intercepted in the case
53 of the presence of plants according to the density, the thickness of the layer and the size leaf foliage. However, in
54 summer, their thermal interest is primarily explained by their ability to reduce the peak of external surface
55 temperatures, their ability to reduce incident radiation on the wall and by cooling the air by evapotranspiration
56 phenomena [15–17].

57 Several studies have shown that the surface temperature under a vegetation layer tends to decrease compared to a
58 conventional envelope without vegetation [8,16,18–21]. Generally, the average superficial temperature difference
59 between inside and outside for a traditional facade can vary between 10 and 60°C. This difference could be lowered
60 to a range of 5 to 30°C by simply using climbing plant on the facades exposed to solar radiation [22]. The difference
61 in temperature depends mainly on the type of plants used, their colour and the density of their leaf layer. It should
62 be noted that it is important to use native plants or plants that can easily adapt to the environment of the building
63 to be vegetalized.

64 In addition to their thermal benefits at urban scale (reduction of the phenomenon of urban heat islands) and
65 optimization of the energy consumption of buildings, vegetalization of building envelopes is increasingly
66 recommended considering their other important potential benefits in terms of reducing airborne sound [23,24]. In
67 terms of storm water retention and decontamination of water runoff, the vegetation also improves the quality of
68 urban air in their ability to fix different pollutants and filtering the surrounding air [25]. It has also shown that
69 vegetation can sustain the building envelope by reducing peaks and temperature fluctuations without causing any
70 potential damage to external façade. Indeed, Ottelé et al. [26] have clearly confirmed that plants can present some
71 risks only in the case of very old surfaces or vulnerable façades which show some deterioration.

72 Although, the research area of vertical green walls is not a new concept. Many researchers started recently to be
73 interested in it, but existing studies showed that the subject is still under development and the various phenomena

74 of heat and mass transfers through a green wall are not yet quite elucidated. Most existing experimental work
75 focused on the effect of vegetated roofs on the building insulation in regions with tropical climate or in the south
76 of Europe, characterized by warm summers and very soft winters [27–34]. The effect of green walls is rarely
77 studied under temperate climate.

78 Most of the works, on the quantification of the impact of green facades on the thermal behaviour of the envelopes,
79 has been much more interested in the extensive type of vegetalized walls (modular panels containing substrate
80 which can accommodate plant species precultured) [35–39]. Extensive Greening Wall type (GW) is relatively very
81 expensive and remains out of reach for most people and therefore their use is generally limited to the facades of
82 large commercial buildings and government buildings.

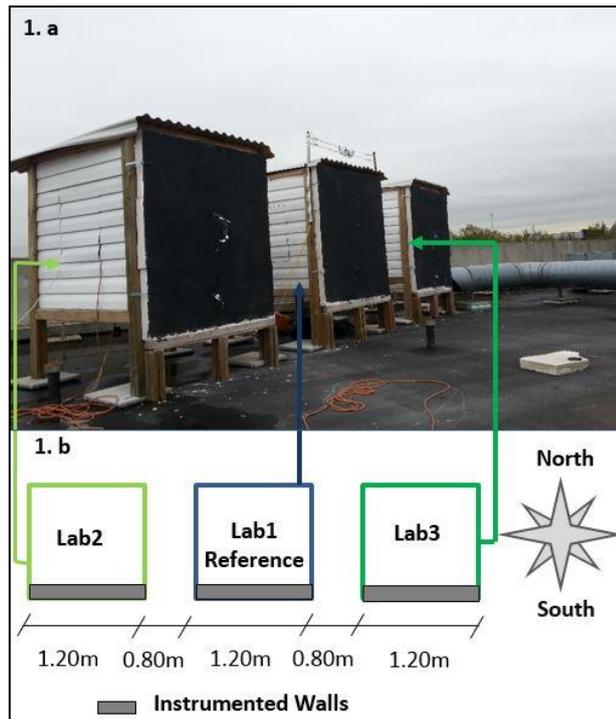
83 It should also be noted that most experiments on the thermal benefits of Living Wall (LW: the simple technique
84 which uses the climbing plants) performed under in-situ conditions, make comparisons between buildings with
85 climbing plants or a complex GW against traditional buildings facades without vegetation [22,40–42]. This is
86 important but the results cannot be generalized, except if all the parameters that can influence the energy balance
87 in the building were considered or measured, which is very complicated to realize. In other words, the different
88 building materials have to be characterized. They also should have the same orders of magnitude in order to
89 quantify only the thermal impact due to the use of plants and do not take that which could be due to a difference
90 of physical and geometrical parameters between buildings or compared facade. It is also recognized that the inside
91 temperatures are strongly influenced by the occupants and their behaviours (cooling and heating system, opening
92 / closing doors and windows, manipulations of windows curtains ...) and it is very difficult to get accurate technical
93 information throughout the year unless the building is pre-equipped with a set of sensors which can collect
94 necessary data. Furthermore, it is not possible to request the same scenarios or modes of use for all occupants of
95 different studied buildings and hence this can generate significant differences and affect the comparisons.

96 This situation led us to investigate the thermal benefits of a simple technique of vegetalization, which could be
97 easily adopted for dwellings. The experimental investigation is based on plant growth where the coverage of the
98 plants is determined experimentally. An occultation percentage is imposed and its impact analysed on the decrease
99 of external surface temperature and heat flux of each prototype. Three identical prototypes are implanted under
100 real conditions and exposed in the same direction in relation to the race of the sun. The physical and geometrical
101 characteristics of the materials used are similar and their values are predetermined.

102 **2. Experimental study**

103 **2.1. Description of the experimental benches**

104 Three identical prototypes with cubical shape, measuring 1.2 m on each side have been designed and installed on
105 the roof of a building in the city of Lille in northern France (50° 38' 2.444" N 3° 2' 48.555" E), to compare the
106 thermal performance of three walls. The first one is used as reference and the two others were in this first stage of
107 the research project equipped with a device which allows imposing a predetermined coverage (percentage of
108 occultation). This coverage was increased gradually on each wall. Then, the prototypes were equipped with two
109 types of green walls, a climbing plant deciduous (Virginia creeper) and another one evergreen (Ivy) to compare
110 their performances with the reference wall. These prototypes represent three identical thermal labs oriented in the
111 same direction (lab1: reference, lab2: located 0.80 m western vs reference, lab3: located 0.8 m eastern vs reference)
112 (Fig. 1). The envelopes were carefully constructed using a waterproof plastic cladding with a thickness of 2.00
113 mm and highly insulated from the inside with a layer of glass wool (100 mm and $\lambda= 0.032$ W/m.K), the bottom
114 and top of each thermal-lab is composed of two plates of light stained wood with a thickness of 20 mm separated
115 by a layer of 100 mm of glass wool. Corrugated plastic panels of 2.00 mm thickness were added to each prototype
116 to protect them against rainfall. As for southern walls, they were made of 100 mm thick-cellular-concrete blocks
117 with $\lambda= 0.11$ W/m.K and were covered with matt black paint to increase solar energy absorption and transfer
118 through these walls opposing the other sides of the “boxes” that have a white reflective coating and were heavily
119 insulated. This has limited the energy exchanges with the outside only at the southern walls. The southern direction
120 was chosen because it allows better capture of solar radiation according to the configuration of our experimental
121 site, therefore the effect of occultation analysis presents the greatest potential to limit overheating during the sunny
122 days.



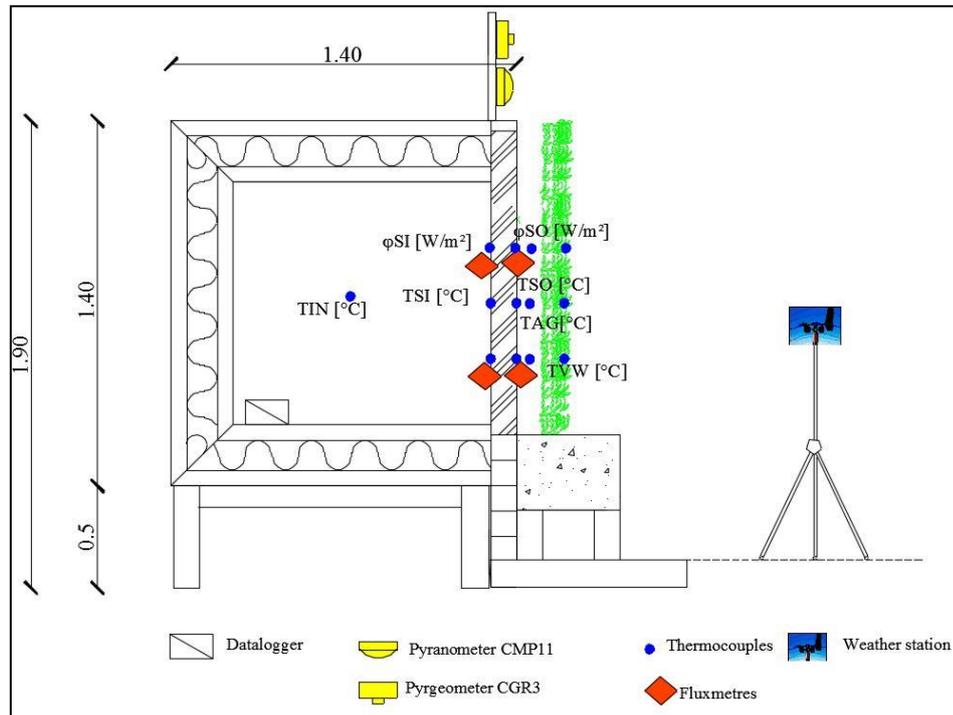
123 **Fig. 1:** Experimental platform, (a): experimental benches viewing design, (b): prototypes disposition on the roof.

124 **2.2. Instrumentation**

125 The southern wall of each thermal-lab was instrumented in order to measure the thermal flux on inside (ϕ_{SI}) and
 126 outside surfaces (ϕ_{SO}). Thermocouples (Type K, accuracy: $\pm 1.5\%$) were used to measure the outside surface
 127 temperature (T_{SO}) and the inside surface temperature (T_{SI}). Each instrumented wall has three different measuring
 128 points in order to avoid the deviation effect and to get better precision below the leaf layer which does not
 129 necessarily have a uniform distribution (irregular geometry of foliage). Four heat flux sensors (Captec[®] instrument,
 130 dim 150x150mm, average sensitivity around $200\mu V / (W/m^2)$, accuracy: $\pm 6\%$) were installed opposite each other
 131 on both sides of each wall to measure the variation of heat exchange flow. A thermocouple (Type K, NF-EN 60-
 132 584 Class 1, accuracy: $\pm 1.5\%$) was placed in the centre of each thermal-lab to record the indoor air temperature
 133 (T_{IN}). Data from incident shortwave radiation (SWR) and incident longwave radiation (LWR) were collected
 134 respectively by a pyranometer (Kipp & Zonen[®] CMP11, sensitivity: $8.64\mu V \cdot W^{-1} \cdot m^{-2}$, accuracy: $\pm 1.4\%$) and
 135 pyrgeometer (Kipp & Zonen[®] CGR3, sensitivity: $14.12\mu V \cdot W^{-1} \cdot m^{-2}$, accuracy: $\pm 6.2\%$). The sensors have been
 136 chosen according to the targeted working values (temperatures, heat flows and radiation) and such as their thermal
 137 response time and sensitivity.

138 The set of sensors was connected to a data-logger (BGP-Q-reader[®], Intelligent Data Logger, accuracy: $\pm 0.01\%$)
 139 and 13 modules with four universal analog inputs-way for each (E-bloxx[®] A4 TC, accuracy: $\pm 0.01\%$). The
 140 sensor information is stored simultaneously and continuously in an interval of five minutes.

141 A weather station (Vantage Pro2®) was installed closed to the three prototypes on the roof of the building to record
 142 the meteorological data conditions: temperature, global solar radiation on a horizontal plane, wind direction and
 143 velocity, relative humidity of ambient air and pluviometry (rainfall). Weather data are collected by the weather
 144 station console located inside lab2 and then synchronized with those recorded by the data-logger. Figure 2 shows
 145 the location of sensors in the thermal labs. All data are collected in our PC laboratory by Ethernet connection for
 146 treatment and analysis.



147 **Fig. 2: Sensors location**

148 **2.3. Validation of the experimental prototypes**

149 The purpose of the validation of the experimental device without vegetation is to analyse whether the three
 150 prototypes have really the same performance under in-situ conditions. Indeed, during the experiment setup, all
 151 efforts were done to conform to the initial design. However, the high sensitivity of the sensors used in thermal
 152 measurements, a possible defect in thermal insulation, air permeability or watertightness integrity in a prototype
 153 compared to another could easily affect the principle of similarity between the three prototypes. This is very
 154 essential in the process of validation tests of imposed coverage rates and also validation of tests on plants.

155 Figures 3 and 4 shows respectively the variations of heat fluxes measured on the external surfaces of the three
 156 walls (ϕ_{SO}), and the outer surface temperature T_{SO} of each instrumented wall.

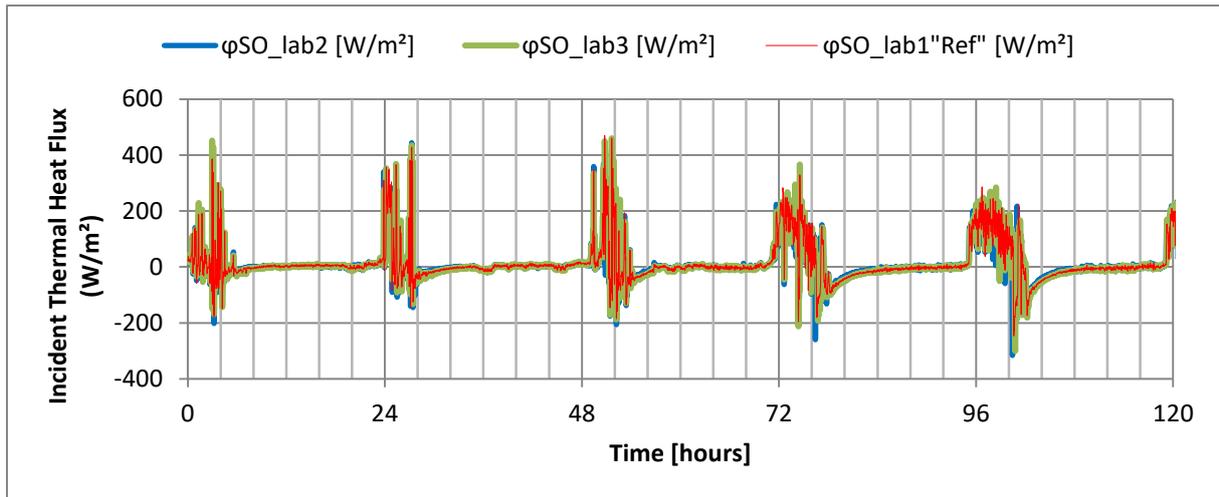


Fig. 3: External thermal heat flux changes on the three thermal-labs.

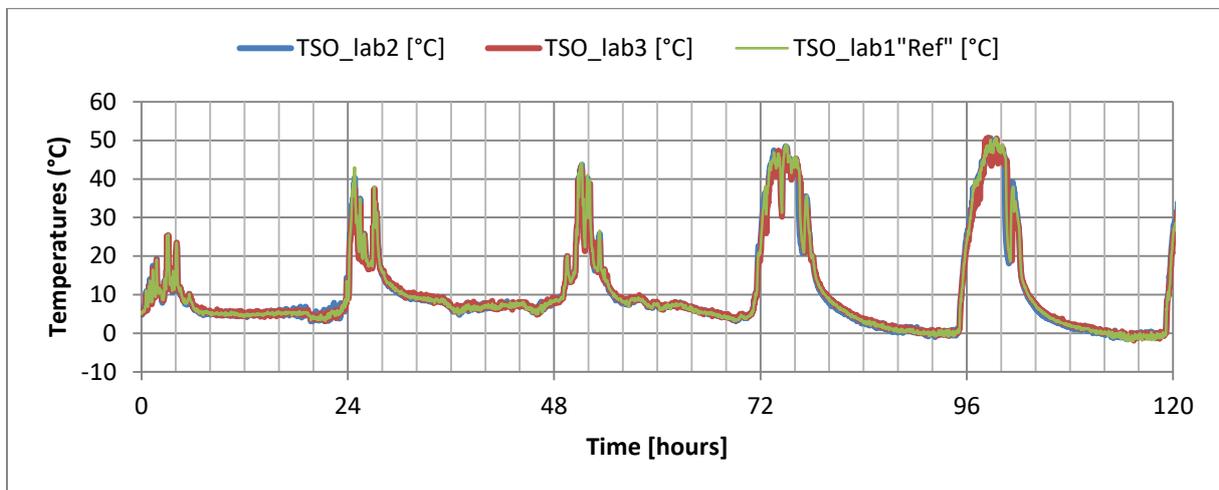


Fig. 4: External surface temperature for the three thermal-labs

158 The tests were conducted during a period of five days from the 6 December to the 11 December 2013, and it was
 159 verified throughout this period that the three walls have the same energy-efficient behaviour. The heat flux and
 160 surface temperature were similar with slight deviations conditions of the order; of +/- 2.48 W/m² for heat flux
 161 measured on outside, of +/- 0.1 °C for temperatures outside surfaces. These deviations are tolerated under in-situ
 162 conditions. It should be mentioned that the inside variation of heat flux and temperatures were verified and they
 163 confirmed the identical behaviour of the prototypes.

164 Once the principle of identical behaviour has been approved, then the evaluation of the impact of the coverage rate
 165 has been initiated, by adding an additional device for masking. The device which was added generates over the
 166 tests, gradual deviations between the reference temperatures and the surface temperatures of the walls which were
 167 equipped by the shading device. So, we can estimate that the differences in flux and temperature measurements
 168 that are obtained, are logically related to the masking device, and not to differences in the initial design of the
 169 prototypes.

170 **3. Tests with imposed cover rates**

171 **3.1. Experimental description**

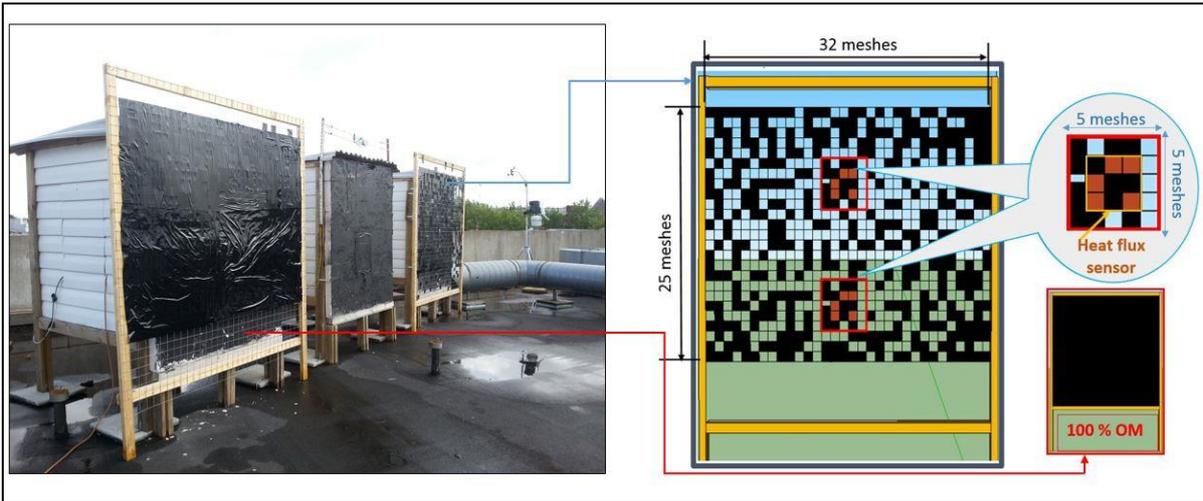
172 The coverage rate term is the most important one in the energy balance equation through foliar layer in numerical
173 models. However, the evaluation of this term in most cases is based on empirical correlations based on the type of
174 vegetation (top, medium, or low) and seasons (winter, spring, autumn and summer) as for example the models
175 developed by [9,43,44]. In the models developed by [44] and [43], the term of the coverage rate was calculated
176 using the method developed by [45]. However, in this study it is aimed to evaluate experimentally the influence
177 of the coverage rates on reducing outer surface temperature and the heat flux balance measured by a vertical wall
178 in function of the imposed coverage rate (occultation rate effect).

179 The experimental method used allows the quantification of the masking effect against incident solar radiation
180 without taking into account other effects of cooling due among other phenomena like the evapotranspiration of
181 plants and moisture transfer. To isolate this shading effect (solar occultation by plant), an inert material with known
182 characteristics and with rapid control of its level of occultation was used. The rapid increase in masking (coverage)
183 would not be possible with leaves of plants because of their very slow growth process (about 2-3 years for a leaf
184 coverage rate of 100% for the ivy and Virginia creeper).

185 Then two screens with square mesh of 5x5cm were installed in front of lab2 and lab3 on-which a rate occultation
186 was imposed artificially. This was defined by counting the total number of stitches on the screens and obscuring
187 the desired percentage of meshes before the heat flow sensors and even the rest of the screen (12.5 meshes were
188 occulted in front of each heat flux sensor and 375 meshes before the remainder of meshes screen for 50% of
189 masking for example). Five sets of measurements were carried out (one week for each set) with increasing
190 coverage rates by 20% on the lab2 for each series of measurements and 10% for lab3. Growing percentage was
191 realized simultaneously and so to keep it doubly proportional on lab2 relative to lab3. Table 1 summarizes the
192 percentage of occultation defined for each test and Fig 5 illustrates the principle of the latest test (100% masking
193 on lab2 / 50% masking on lab3).

194 **Table 1:** Imposed occultation percentage and test process

Periods of test	Lab2		Lab1 « ref »		Lab3	
Experiment 1: 15 th April 2014 to 21 st April 2014	Total Occulted Meshes		Total Occulted Meshes		Total Occulted Meshes	
	(OM) = 20%		(OM) = 0%		(OM) = 10%	
	OM around sensors	Total OM	OM around sensors	Total OM	OM around sensors	Total OM
	5	155	0		2.5	77.5
Experiment 2: 22 nd April 2014 to 27 th April 2014	Total OM = 40%		Total OM= 0%		Total OM= 20%	
	OM around sensors	Total OM	OM around sensors	Total OM	OM around sensors	Total OM
	10	310	0		5	155
Experiment 3: 28 th April 2014 to 2 nd may 2014	Total OM= 60%		Total OM = 0%		Total OM = 30%	
	OM around sensors	Total OM	OM around sensors	Total OM	OM around sensors	Total OM
	15	465	0		7.5	232.5
Experiment 4: 3 rd May 2014 to 8 th may 2014	Total OM = 80%		Total OM = 0%		Total OM = 40%	
	OM around sensors	Total OM	OM around sensors	Total OM	OM around sensors	Total OM
	20	620	0		10	310
Experiment 5: 9 th May 2014 to 15 th May 2014	Total OM= 100%		Total OM = 0%		Total OM = 50%	
	OM around sensors	Total OM	OM around sensors	Total OM	OM around sensors	Total OM
	25	775	0		12.5	387.5

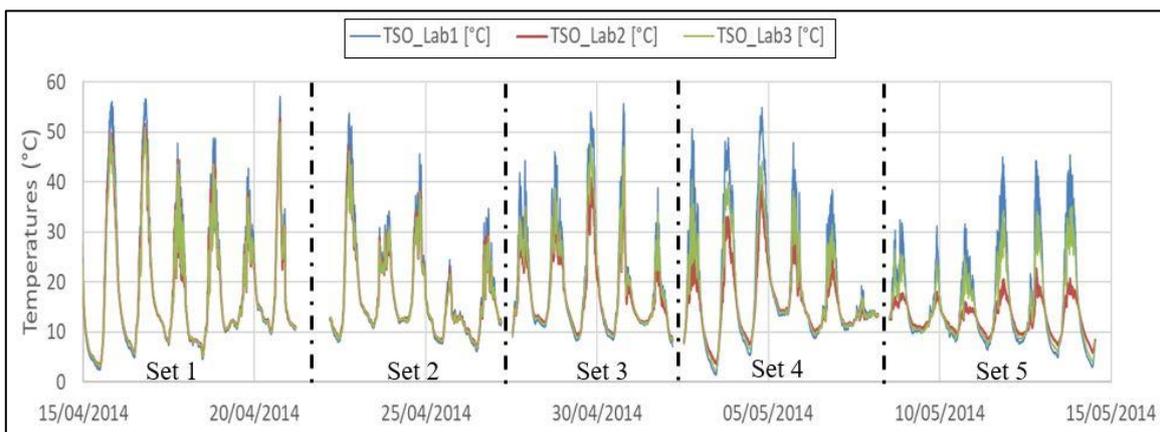


195 **Fig. 5:** Principle of the latest test (100% masking on lab2 / 50% masking on lab3).

196 **3.2. Experimental results**

197 Tests began on 15th April 2014 and occultation percentages were varied from 20 to 100% for lab2 and from 10 to
 198 50% for lab3 (Fig. 5). Changes in outside measured thermal heat flux and outer surface temperature were recorded
 199 in intervals of five minutes and compared with the external heat flow and outer surface temperature of lab1 (Ref)
 200 as the occultation rate was increased.

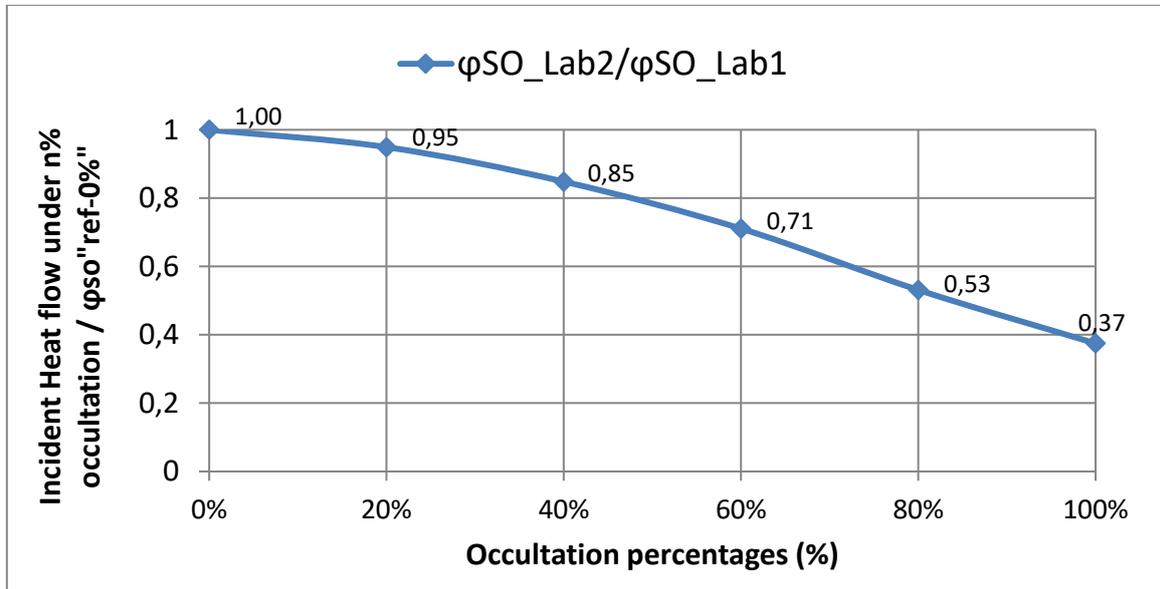
201 Figure 8 compares the temperature variations of surfaces under different coverage rates to the temperatures of the
 202 reference.



203 **Fig. 6:** Variation of outside surface temperatures of the three instrumented walls (values of coverage
 204 rate are detailed on the table 1 for each set of measurement)

205 As the coverage rate increased, significant reductions in surface temperatures were recorded. The decrease in
 206 external surface temperatures is a direct consequence of the limitation of heat fluxes from solar radiation by
 207 masking.

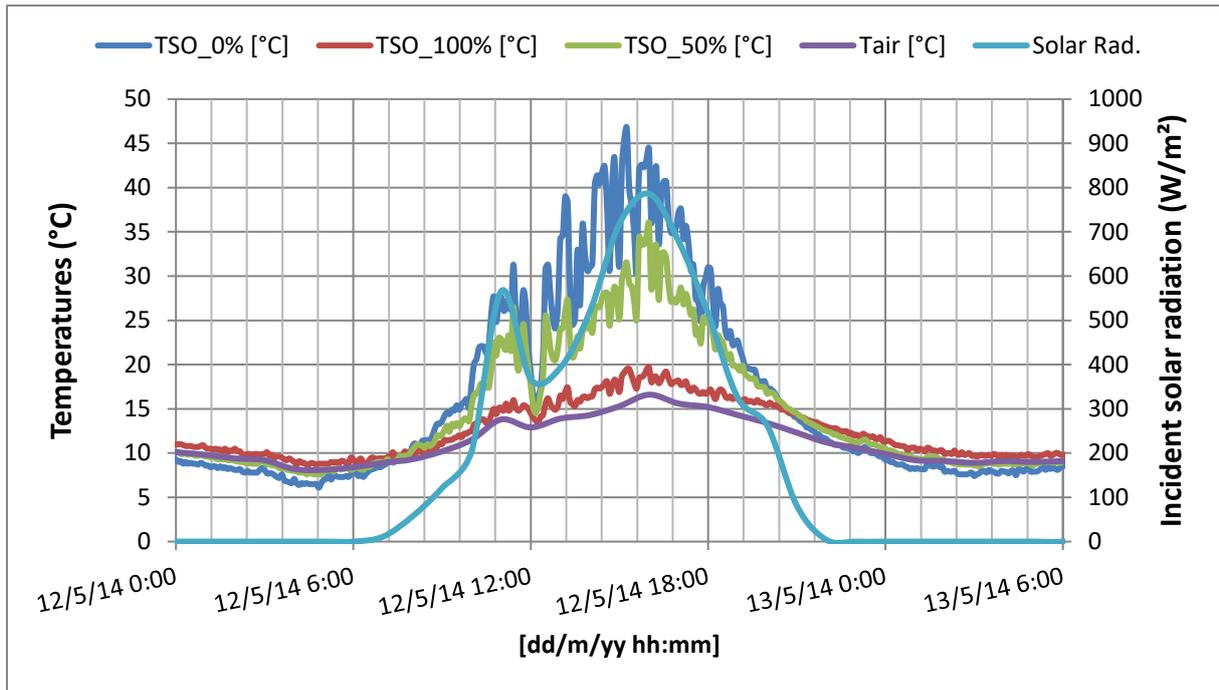
208 Indeed, it was found that the received thermal heat flux decreased in proportion to the increase of the occultation
 209 percentages imposed on the instrumented walls of lab2 and lab3. The incident thermal heat flux was reduced by
 210 5%, 15%, 29% and 46% under coverage rate of 20%, 40%, 60% and 80%, respectively. The reduction of thermal
 211 heat flux was 63% under full masking (Fig. 7).



212 **Fig.7:** Thermal heat flux decrease in proportion of coverage rates.

213 These results (Fig. 7) were obtained by calculating the ratio of the thermal heat flux received by the instrumented
 214 lab2 wall and that received by the reference wall during the presence of the solar radiation (only during the day).
 215 For each test around 2016 values were stored and were then averaged and plotted to obtain an overall representation
 216 of the impact of the coverage rate.

217 The comparison between the temperature variations for the 5th test (OM-lab2:100%, OM-lab1:0%, OM-lab3: 50%)
 218 shows clearly the importance of the masking effect on the decrease of the outer temperatures surfaces (Fig. 8).
 219 Indeed, a reduction of the outer temperature surface compared to the outer temperature surface of the reference
 220 wall (lab1) by 10°C was recorded under a coverage rate of 50% and by 20°C for a complete occultation rate. The
 221 outer temperature surface of reference wall (Lab1) reached 48°C as a maximum temperature while the external
 222 temperature surface below 50% of occulted meshes didn't exceed 38°C. The superficial temperature on the outside
 223 of lab2 didn't exceed 20°C under a coverage rate of 100%. As for the surface temperature under a coverage rate
 224 of 100%, it was slightly above the air temperature throughout the day. This shows the effectiveness of masking to
 225 limit overheating during a sunny day (the temperature differences mentioned correspond to the maximum of solar
 226 radiation reaching the 786 W/m²).



227 **Fig. 8:** Outside surface temperature variations under different occultation rates.

228 Furthermore, once the database has been made with artificial material, the masking device has been replaced by
 229 two kinds of climbing plant in order to compare their effects with the reference wall.

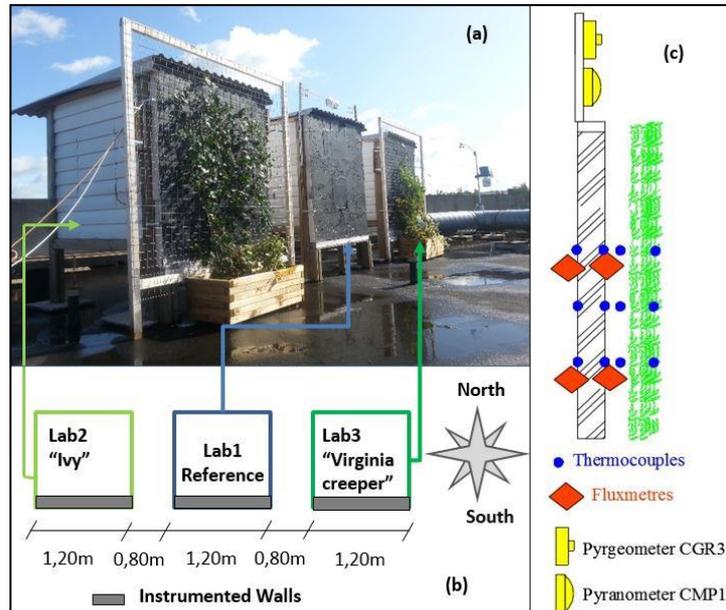
230 In other terms, the first experiment has shown the effect of a masking made by an artificial material. In the second
 231 one, the artificial masking device was replaced by a real vegetation. Then, the natural growth of the plants was
 232 evaluated by an image processing method which made it possible to determine the coefficient of the coverage rate
 233 which will be necessary to feed any theoretical model or numerical calculation of the energy balance of the facade.

234 **4. Test with vegetation**

235 **4.1. Experimental approach**

236 The second experiment (test with vegetation) presents the evaluation of the energy effect of a solar mask created
 237 by a VW. The aim is to evaluate the impact of vegetation on the thermal performance of building envelope under
 238 a temperate climate, in summer and winter. In the first experiment the southern wall of each prototype (the cubic
 239 cells of reduced size) was equipped with a device simulating the masking effect of a vegetal cover by an artificial
 240 material [17]. These cubic cells of reduced size each consisted of five thermally insulated walls and a test wall,
 241 facing south, equipped with heat flux and temperature sensors (see detailed description on 2.1). They are now
 242 equipped with vegetalized walls (Fig.9). The central prototype "Lab1" serves as a reference, while Lab2 and Lab3
 243 are respectively equipped with an evergreen (Ivy) plant and a deciduous plant (Virginia creeper). The idea of the

244 use of a deciduous plant and another evergreen is due to the fact that, the persistent leaves can have a negative
 245 impact on energy consumption during winter under a temperate climate. While the deciduous plant can allow the
 246 façade to benefit from solar radiation in winter and limit summer overheating.



247 **Fig. 9:** Test of masking by the vegetation; (a) general view; (b) distribution of vegetated walls; (c) sensors
 248 disposition.

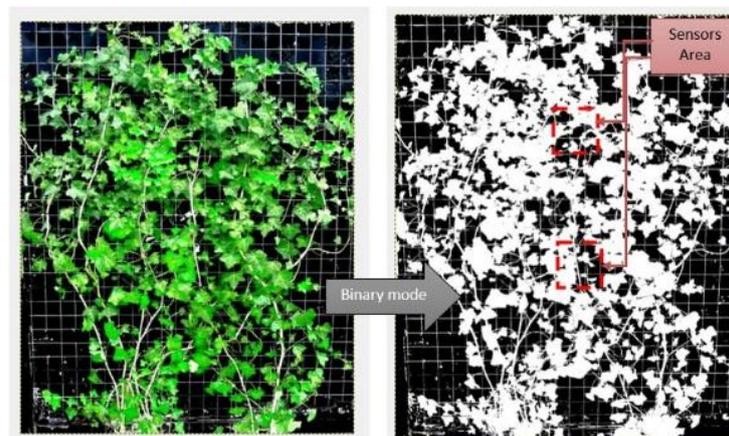
249 *4.2. Determination of the coverage rate*

250 In order to determine the masking rate of the vegetal walls composed of ivy or Virginia creeper, an analysis of the
 251 photographs taken monthly was undertaken. To explain the procedure, Figure 10 was selected. It was taken at the
 252 beginning of October 2014, more than four months after planting of "ivy". The selected period also corresponds
 253 to the validation period of the theoretical model presented previously.



254 **Fig. 10:** Plant growth monitoring by camera

255 An image processing software "ImageJ" [46] was used to determine the percentage of plant occultation of the
256 instrumented "South" walls of the cells. ImageJ, is an image analysis program that can calculate surfaces and
257 measure distances between objects within an image. The process is based on the recognition of information
258 characteristic for each pixel composing a photo. Indeed, for the image to be stored in a digital medium, it is first
259 necessary to divide the image into small cells called "pixels". A grid of pixels is then constituted, so that each of
260 the pixels is itself a small rectangle. Once this is done, the storage medium assigns to each of the pixels numerical
261 values corresponding to their colours. Depending on the image quality, the number of usable numerical values is
262 very variable, it can reach a maximum of 2^{24} different colours that can be displayed on a computer. For the simplest
263 case, such as grayscale images, the numerical values are between 0 and 255. Conventionally, the 0 represents the
264 black colour, and the 255 is attributed to the white colour. The values between the two terminals allow the
265 representation of shades of grey. The realization of the measurements on the objects of an image, then depends on
266 the counting of the pixels composing it [46–48].
267 For an object to be recognized as a single entity, it must be composed of pixels of the same colour. By way of
268 example, the plant leaves in the previous image (Fig.10) are recognized by the program as several objects according
269 to the levels of brightness and contrast of the green colour. A pre-treatment is necessary to isolate the colours on
270 which the measurements will be made. The resulting image was then converted to binary (black and white only)
271 for the measurement (Fig.11).



272 **Fig. 11:** (a) pre-treatment of colours; (b) binary conversion
273 To determine the coverage rate on the image in binary mode (Fig.11 (b)), it is sufficient to know the actual sizes
274 of the image (in centimetres), its dimensions expressed in pixels, and then the number of white pixels "255" is
275 calculated by the software. The real dimensions taken on the experimental benches were introduced into the
276 software as they are necessary to express the pixel size in unit of length. The coverage rate obtained on the overall

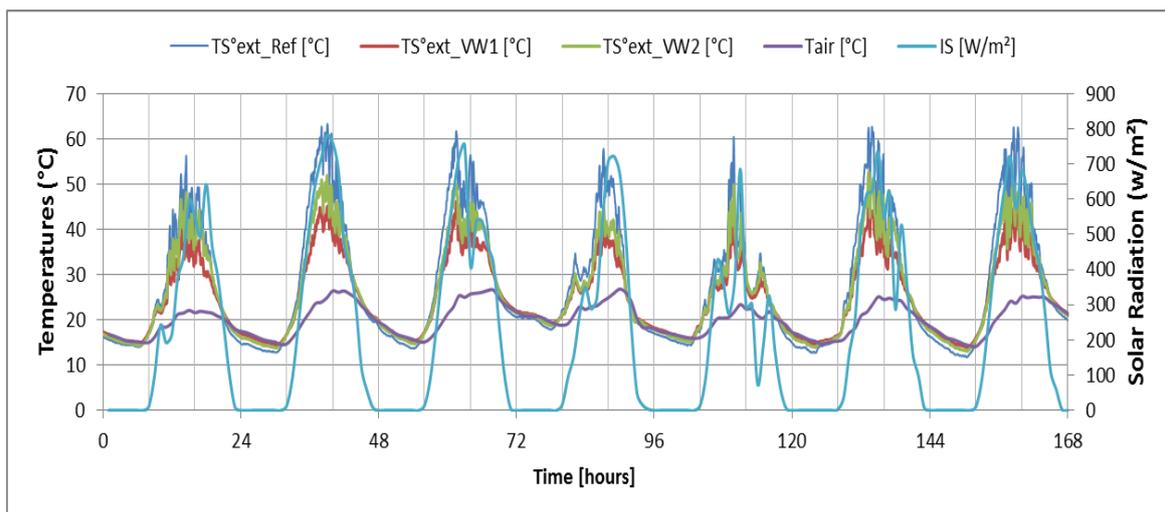
277 image presented here was 51%. In the measurement area (flow sensors), the coverage rate obtained was 45% which
278 can represent the occultation rate for a validation of a theoretical model.

279 5. Experimental analysis of plants occultation effects

280 The aim was to follow over time the incidence of vegetalized walls in a temperate climate. Ivy has the characteristic
281 of preserving its foliage throughout the year and it has been the subject of an experimental follow-up in summer
282 and in winter. Unlike ivy, the growth cycle of the Virginia creeper is characterized by a loss of foliage during the
283 winter and a very rapid regrowth in summer. During the summer, attention has been focused to assessing the
284 limitation of summer overheating with both plants, while in winter the impact that plants may have had on
285 temperature surfaces was discussed. During the winter, the comparison between the variation in the temperatures
286 of the exterior surfaces of the walls equipped with ivy and the Virginia creeper allowed the evaluation of whether
287 the use of VW in a temperate climate will provide more thermal comfort by limiting thermal losses, or if its use
288 will have a negative impact by limiting the solar gain throughout cold days.

289 5.1. Thermal effects in summer

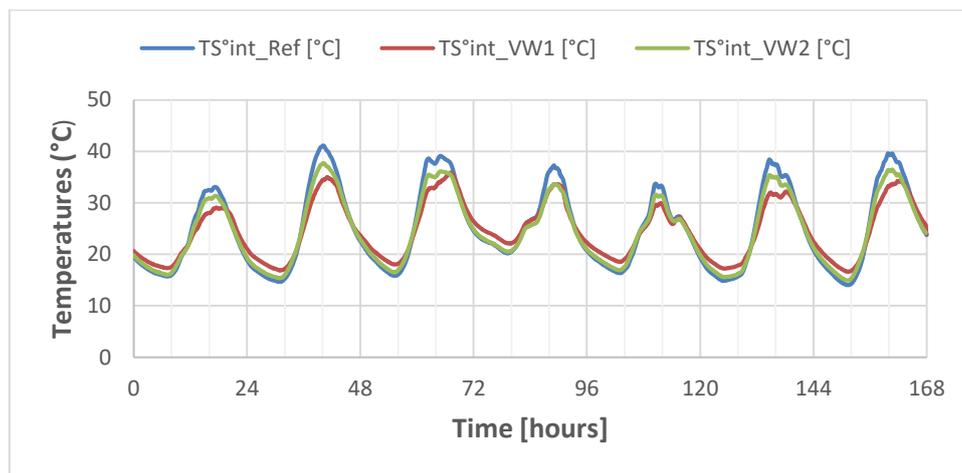
290 In summer, the sequences were selected according to the air temperature peaks and the maximum values of the
291 incident solar radiation recorded during the summer of 2014. Figure (12) compares the temperatures of the outside
292 surfaces of the instrumented walls (TS ° ext_VW1: ivy, TS ° ext_VW2: Virginia creeper) to those of the reference
293 wall (TS ° ext_Ref).



294 **Fig. 12:** Comparison of external surfaces temperatures (reference / VW1 / VW2) in summer.

295 During the period from 30 July to 05 August 2014, the maximum solar radiation values recorded by the
296 meteorological station at the experimental site varied between 640 and 781 W/m². As for the air temperatures, they

297 fluctuated between 14°C and 27 °C. Under the aforementioned solar radiation peaks, temperatures on the outer
 298 surface of the control wall, were on average, higher than 60°C. With both walls having vegetation coverings, the
 299 outside surface temperatures under the radiation peaks were limited to 44°C and 50 °C for VW1 and VW2
 300 respectively. Although the cover percentages were relatively low during this period, significant temperature
 301 differences were observed. In fact, the ivy had a coverage ratio of only 41%, and reduced the temperature peaks
 302 of outside surface by 15°C. The Virginia creeper, with its 28% coverage, has lowered the outdoor surface
 303 temperature by 10°C.
 304 Furthermore, during the night it was observed that the outside surface temperatures of the reference wall were 1.5
 305 °C and 1°C, on average, lower than the VW1 and VW2 respectively. The presence of vegetated walls does indeed
 306 limit thermal losses by infrared radiation. The reductions in outside surface temperatures confirm the important
 307 role of plant in limiting summer overheating. Their repercussions on the temperature variations inside the cells can
 308 be shown in figure 13.

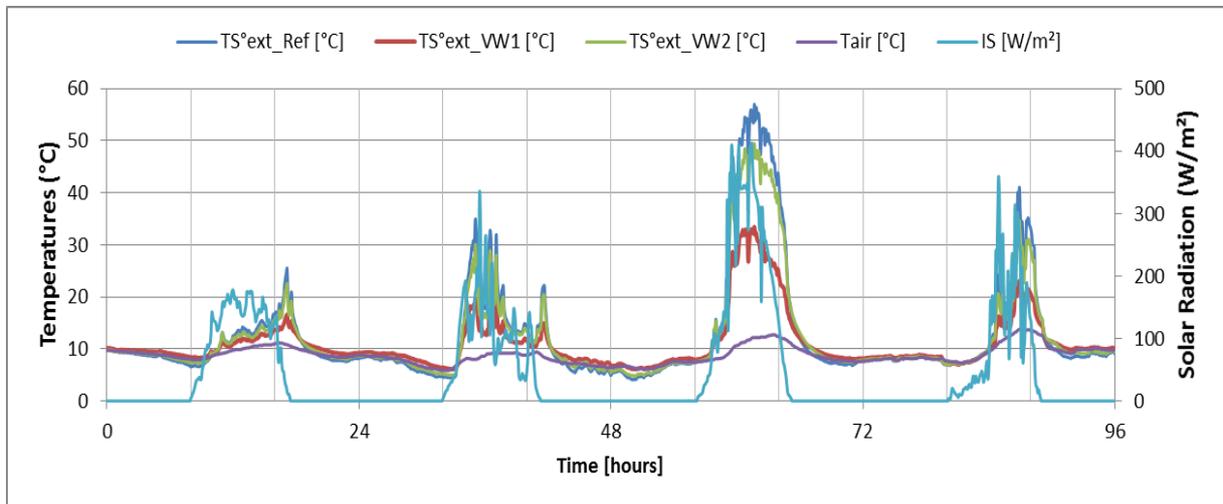


309 **Fig. 13:** Comparison of internal surfaces temperatures.
 310 Indeed, the interior surface temperatures of the reference wall which corresponded to the peak periods fluctuated
 311 between 33°C and 41°C. At the same time, they did not exceed 29°C and 35°C for the VW1. For the VW2, the
 312 impact on the temperatures of the interior surface has been less affected. These were between 31°C and 37 °C.
 313 During night period, due to the limitation of thermal losses by infrared radiation, the interior surface temperature
 314 of VW2 was about 2°C higher than the reference wall.

315 **5.2. Thermal effects in winter**

316 During the winter period, four days in November were selected to present the analysis of the thermal effects of the
 317 vegetalized walls. The first two days had a cloudy sky with very low radiation levels. As for the last two, the
 318 intensity of the solar radiation was relatively high compared to the seasonal average usually recorded in the city

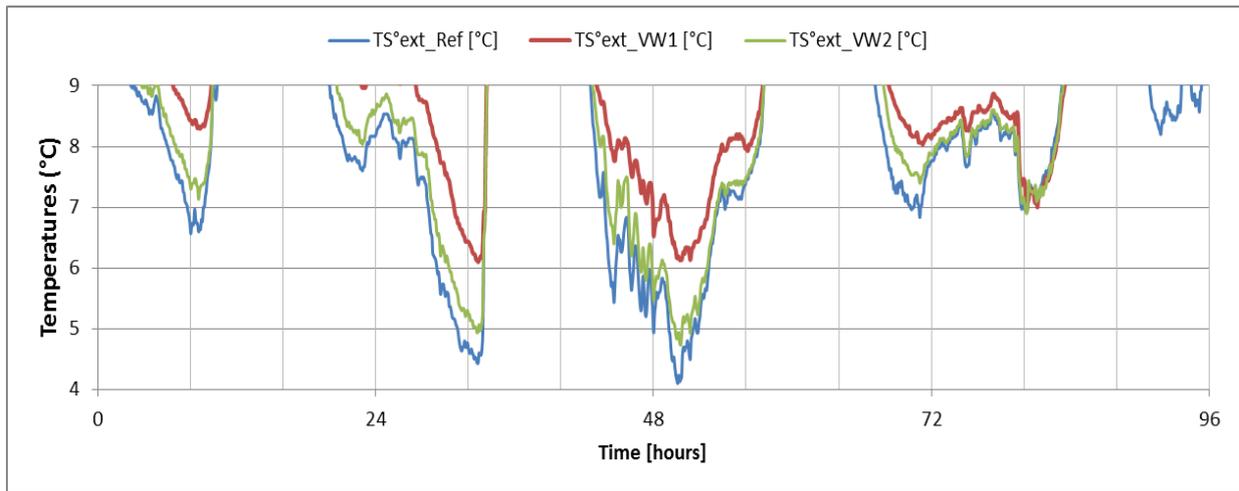
319 of Lille. During this period, the cover rate of the two vegetalized walls was 55% and 15% for ivy (VW1) and
 320 Virginia creeper (VW2), respectively. The recorded variations of the different surface temperatures according to the
 321 solar radiation and the outdoor ambient air temperature are given in figure 14.



322 **Fig. 14:** Comparison of external surfaces temperatures (reference / VW1 / VW2) in summer.

323 During the first two days, average solar radiation "in peak periods" was between 162 W/m² and 147 W/m², and
 324 ambient air temperatures ranged between 6°C and 11.2°C. The temperatures of the outer surface of the reference
 325 wall coinciding with the peaks of solar radiation reached 17°C. In the presence of the vegetalized walls, these were
 326 slightly reduced by the plants, they were in average at 13.1°C and 15.7°C for the VW1 and VW2 respectively. In
 327 a period of low sunshine, the vegetalized walls prevents narrowly the exterior facades from solar energy gain.
 328 Outdoor surface temperatures were reduced by 3.9° C in VW1 and 1.3 °C by VW2. As for the last two days, during
 329 which solar radiation was relatively high (about 400W/ m²), ambient air temperatures varied between 6°C and
 330 14°C. The presence of ivy reduced the outside surface temperatures of VW1 by about 23°C (peak period) in
 331 comparison with the reference wall. The surface temperature of this wall reached 55°C during peak periods. Unlike
 332 ivy with a coverage rate of 55%, the Virginia creeper reduced the outside surface temperature of VW2 by only
 333 9°C. The low coverage rate of the Virginia creeper allowed the VW2 to benefit from the solar energy. Its surface
 334 temperature reached a maximum of 46°C instead of 32°C for the VW1.

335 Moreover, during the nocturnal periods, the presence of the ivy limited the thermal losses of the VW1. Its outdoor
 336 surface temperature was during the nocturnal periods, in average, 1.3°C higher than the temperatures measured on
 337 the outer surface of the control wall. The Virginia creeper, for its part, limited the nocturnal cooling by only 0.4°C
 338 (Fig. 15).



339 **Fig. 15:** Zoom on night-time variations of external surfaces temperatures - see Fig. 14.

340 Finally, it should be noted that in the case of full growth of the foliage coverage, the thermal effects could be more
 341 significant. These, could not be studied experimentally due to the slow growth of plants. They could be highlighted
 342 in the future through numerical simulations (future publication).

343 6. Conclusion

344 The research presented here has highlighted the thermal interest of simple vegetalized walls. The experimental
 345 results presented in this paper showed clearly the effect of masking on reducing surface and air temperatures. It
 346 was found a significant decrease in the thermal heat flux through the south oriented wall depending on the increase
 347 of the coverage rates. Accordingly, this allowed reducing outside surface temperatures and enhancing interior
 348 comfort in the thermal labs with masking screen. The measurements also highlighted the effects of masking by the
 349 plants on the limitation of summer overheating. It should be emphasized that the first measurements were taken
 350 on a masking process with an inert material (black plastic film) and not on leaf of plants. This allowed controlling
 351 the coverage rates and varying them, rapidly on the one hand and separating the effects of plants due only to
 352 shading from those due to other phenomena. A very rich database could be constituted over a very short span of
 353 time compared to a real test on a living material that develops slowly (plant growth).

354 The second experiment presents a new contribution to experimental evaluation of the thermal effects of vegetalized
 355 walls. The experimental results analysis required knowledge of the coverage rate relative to the vegetalized wall
 356 during each analysed sequence. The approach used to estimate the coverage rates, using images taken throughout
 357 the experiment, was presented.

358 In addition, the experimental monitoring helped to highlight the effects of plants during winter and summer
 359 periods. During winter, the presence of plants played a rather "negative" role by limiting solar energy gains.

360 Nevertheless, this negative role is attributed to plants only on sunny days. Indeed, during the nocturnal periods,
361 the results showed that the plants give the CC walls a slight insulating capacity by the limitation of the thermal
362 losses. As for the summer period, despite the low coverage rates obtained experimentally, the results showed that
363 the plant screens could play an equivalent role to that of an additional layer of material to the CC walls. The plants
364 thus allowed an increase in the overall thermal resistance of the CC walls. The experimental approach undertaken,
365 demonstrated the thermal interest of simple vegetalized walls. This will allow future modelling of the thermal
366 effect of plants on buildings at prototype and real scale.

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