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# Impact of plants obscuration on energy balance: theoretical and numerical study

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## Abstract

This paper presents the evaluation of the energy effect of a solar mask created by a vegetalized wall on the thermal performance of a building envelope in a temperate climate. The paper describes mainly the adaptation of a simplified prediction model. The method remains similar to the occultation by an artificial material, however, some considerations related to the plants characteristics was incorporated such as: the semi-transparent aspect of the foliage plants and their geometrical distribution. The simplified model has been developed and validated on the basis of tests carried out with a controlled occultation experimental set-up. This device was then used for the experimental monitoring of the impact of two types of plant: ivy and Virginia creeper. The coverage rate was determined using an image analysis process, which allowed the comparison of the tests with the theoretical results. The numerical prediction was very close to the experimental values, and the average error was about 1.5°C. Finally, an experimental analysis of the effects of deciduous plants and another evergreen was carried out. The deciduous plant allowed the facade to benefit from solar radiation in winter. While the persistent leaves have better limited summer overheating.

**Keywords:** vegetalized walls, obscuration effect, model adaptation, thermal effect analysis.

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## 24 Nomenclature

### Symbols :

$T$	temperature, K
VW	vegetalized wall
$I_s^\downarrow$	incident solar radiation, $W/m^2$
$I_r^\downarrow$	infrared radiation, $W/m^2$
$c_p$	specific heat, $J.kg^{-1}.K^{-1}$
$d_o$	height of movement, m
$df$	average leaf thickness, m
$F$	leaf cover index
$h_{cv}$	convective exchange coefficient, $W.m^{-2}.K^{-1}$
$hf$	height of vegetal canopy, m
$k$	constant of Von Karman
$ra$	aerodynamic resistance, $s.m^{-1}$
$rc$	« resistance » to sensible thermal transfer, $s.m^{-1}$
$uc$	flow velocity within the plant layer, m/s
$U_m$	wind speed, m/s
$z_{0H}$	roughness lengths « sensitive heat », m
$z_{0m}$	roughness lengths « amount of movement », m

### Greek letters :

$\alpha$	solar absorption coefficient
$\beta_{zen}$	solar zenith angle
$\varphi$	flux density, $W/m^2$
$\sigma$	constant of Stefan-Boltzmann, $5.67 \times 10^{-8} W/m^2.K^4$

$\sigma_{occ}$	coverage rate, [0,1]
$\varepsilon$	emissivity, [0,1]
$\tau$	transmissivity, [0,1]
$\sigma_{vw}$	coverage rate, [0,1]
$\mu^*$	solar extinction coefficient

### Indices / Exponents :

CC	cellular concrete
vw	vegetalized wall
Eq	equivalent
sol	solar
$R_{env}$	infrared exchanges with the environment
$R_{occ}$	infrared exchanges with the VW
$R_{env}$	infrared exchanges with the environment
$R_{occ}$	infrared exchanges with the VW
$R_{env-vw}$	infrared exchanges with the environment
$R_{cc-vw}$	infrared exchanges with the vegetalized wall
cv	convection
tr	transmitted
th	theoretical
AG	air gap
SWR	short-wave radiation, $W/m^2$
LWR	long-wave radiation, $W/m^2$

## 25 1. Introduction

26 The issue of reducing energy consumption is a major factor in solving contemporary environmental problems.  
 27 From the first world conference on the environment (Stockholm, 1972) to the recent climate conference (Cop 21,  
 28 Paris 2015), passing by the Kyoto agreements (1997) and the various inter-state negotiations around the world,  
 29 the building sector has been identified as one of the most important targets on which energy saving efforts must  
 30 be made [1]. The vegetation of building envelop by creating Vegetalized Walls or Vegetal Walls (VW) is among  
 31 the various solutions for the optimization of energy consumption in buildings and some well mediatised projects  
 32 have given a very good image of the process (Quai Branly Museum in Paris for example [2]). This tendency  
 33 mainly came from Germany in the early 1970s. Although it is a very old technique, the main driver of its

34 development remains, to this day, the aesthetic aspect and the desire to provide originality to buildings [3].  
35 However, green walls can also have very positive effects on the improvement of the sound insulation [4–6] and  
36 the thermal performance of buildings [7–16]. According to numerous studies, green walls contribute to the  
37 improvement of air quality [17–21], bring biodiversity to urban centres and limit the development of the heat  
38 island phenomenon [22–25].

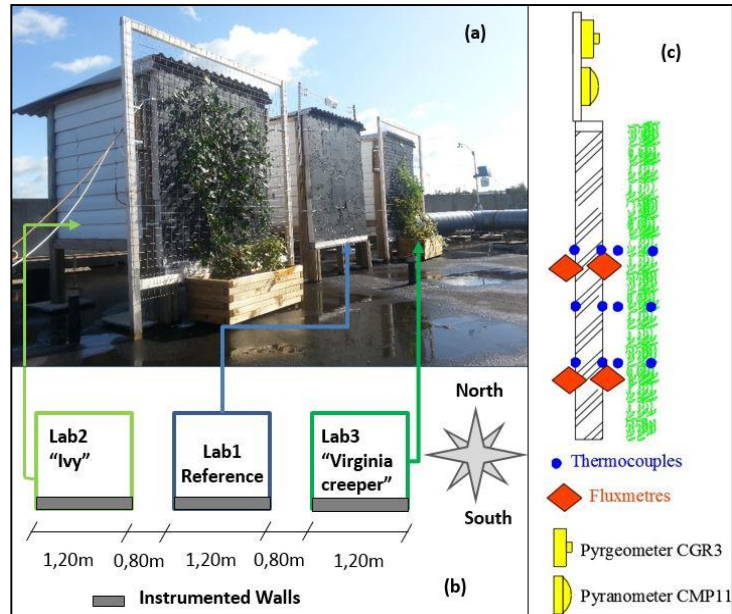
39 It is notable, however, that up to now there are very few studies proposing tools for evaluating the thermal effects  
40 of green walls on buildings [26].

41 The experiment have shown the effect of a masking made by an artificial material [27]. A simplified model was  
42 developed on the basis of this experiment, which allowed the theoretical evaluation of the thermal impact of an  
43 artificial masking according to its coverage rate. The artificial masking device was replaced by real vegetation  
44 and the theoretical study was supplemented by a model, which is more adapted to the case of masking by  
45 vegetation. The natural growth of the plants was evaluated by an image processing method, which made it  
46 possible to determine the coefficient of the coverage rate [27]. The differences between artificial masking and  
47 another with plants are discussed and interpreted as new parameters in the different equations. This work aims to  
48 evaluate the thermal impact of "simple" VW by numerical and theoretical tools. The paper presents the modelling  
49 of the thermal effect of plants on buildings at prototype and real scale.

## 50 **2. Methods**

### 51 *2.1. Experimental approach*

52 This part presents the evaluation of the energy effect of a solar mask created by a VW [27]. The aim was to  
53 evaluate the impact of vegetation on the thermal performance of building envelope under a temperate climate, in  
54 summer and winter. This wall was equipped with a device simulating the masking effect of a vegetal cover by an  
55 artificial material. This approach allowed the listing and evaluation of the principal transfer phenomena that  
56 occur between the wall and its environment. Thus, a relatively simplified model has been validated from the  
57 comparison between numerical simulations and experimental results obtained for the thermal labs which are  
58 under natural constraints. These cubic cells of reduced size each consisted of five thermally insulated walls and a  
59 test wall, facing south, equipped with heat flux and temperature sensors (see detailed description on part 1). They  
60 are now equipped with vegetalized walls (Fig.1). The central prototype "Lab1" serves as a reference, while Lab2  
61 and Lab3 are respectively equipped with an evergreen (Ivy) plant and a deciduous plant (Virginia creeper).

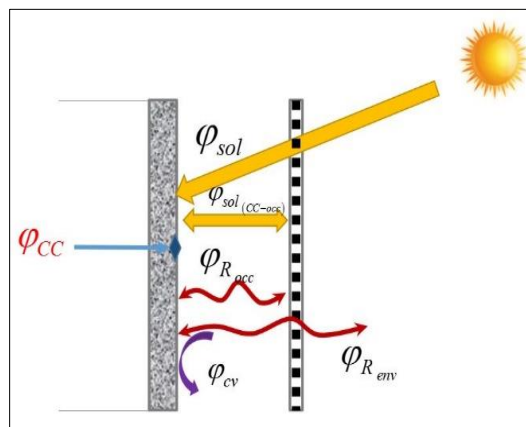


62 **Fig. 1:** Test of masking by the vegetation ; (a) general view ; (b) distribution of vegetated walls ; (c) sensors  
 63 disposition.

64 The experimental results [27] showed clearly the effect of masking on reducing surface and air temperatures. It  
 65 was found a significant decrease in the thermal heat flux through the south oriented wall depending on the  
 66 increase of the coverage rates.

67 **2.2. Preliminary Theoretical model**

68 A preliminary theoretical model has been developed to identify the parameters that affect the heat flow received  
 69 by an occult wall. This model was created by performing an energy balance to determine the heat flux resulting  
 70 from various transfer phenomena between the outer wall and the environment, which are conditioned by the  
 71 presence of a partial occultation (Fig. 2).



72 **Fig. 2:** Energy balance at the outer surface of the CC wall.

73 **2.2.1. Energy exchange balance**

74 The heat flux at the outer wall ( $\varphi_{CC}$ ) obtained by the balance of the radiative and convective exchanges SWR and  
 75 LWR, can be written in the following form:

$$76 \quad \varphi_{CC} = \varphi_{sol} - \varphi_{R_{env}} - \varphi_{R_{occ}} - \varphi_{cv} \quad (1)$$

77 The different terms of the energy exchange balance at the CC wall are detailed below (2.2.2. to 2.2.4.). The  
 78 transfer equations used are relatively standard in the bibliography [28], the characteristic term of the coverage  
 79 rate was added here in correspondence with our study. The radiative characteristics of each of the materials used  
 80 are given in Table 2.

81 Table 2 : Radiative properties

Radiative Properties	$\alpha$	$\varepsilon$	$\tau$	r
Wall CC	0.9	0.9	0	0.1
Masking	0.9	0.9	0	0.1

82 Calculations were made using meteorological records and measured temperatures on the CC wall surfaces,  
 83 within the shading device and the air gap.

84 **2.2.2. Solar radiation**

85 The radiation absorbed by the outer surface of the wall is equal to the difference between the radiation which  
 86 passes through the uncovered part of the occultation  $Is^\downarrow \cdot (1 - \sigma_{occ})$  and the radiation reflected by the wall.

$$87 \quad \varphi_{sol} = \alpha_{CC} (1 - \sigma_{occ}) \times Is^\downarrow \quad (2)$$

88 The SWR radiative exchanges between the masking and the outer surface of the cellular concrete are represented  
 89 by the solar radiation of equation (2), and equation (3) takes into account possible multiple reflections between  
 90 the wall and the inner surface of the masking.

$$91 \quad \varphi_{sol(occ-CC)} = Is^\downarrow \cdot \alpha_{CC} (1 - \sigma_{occ}) \times \sum_{n=2}^{\infty} r_{CC}^n (\sigma_{occ} \cdot r_{occ})^{n-1} \quad (3)$$

92 The value of  $n = 2$  is largely sufficient here, the surfaces having high solar absorption coefficients (close to 0.9).

93 **2.2.3. Infrared radiation**

94 The radiation (LWR) at the CC wall is the sum of the exchanges between the wall and the environment is  
 95  $(\varphi_{R_{env}})$ , and between the wall and the masking is  $(\varphi_{R_{occ}})$ .

$$\varphi_{R_{env}} = \frac{\varepsilon_{CC} \sigma \cdot (T_{CC}^4 - T_{EQ}^4) \times (1 - \sigma_{occ})}{1 - \sigma_{occ} \cdot (1 - \varepsilon_{CC})} \quad (4)$$

96

97 The exchanges between the CC wall and the environment are calculated from an equivalent temperature  
 98 determined using a pyrgeometer placed on a vertical wall and which integrates the combined effect of the  
 99 “surfaces” constituting the radiative environment at low temperatures (sky, ground, etc.). The equivalent  
 100 temperature is obtained by equation (5).

$$T_{EQ} = \left( \frac{I_r}{\sigma} \right)^{\frac{1}{4}} \quad (5)$$

101

102 The radiative exchanges LWR between the masking and the CC wall are represented by the following equation:

$$\varphi_{R_{occ}} = \frac{\sigma \cdot (T_{CC}^4 - T_{occ}^4)}{\frac{1 - \varepsilon_{CC}}{\varepsilon_{CC}} + \frac{1}{\sigma_{occ}} + \frac{1 - \varepsilon_{occ}}{\varepsilon_{occ}} \times \frac{1}{\sigma_{occ}}} \quad (6)$$

103

#### 104 **2.2.4. Convection**

105 The heat flux exchanged by convection ( $\varphi_{cv}$ ) is given by the following equation:

$$\varphi_{cv} = h_{cv} \cdot (T_{CC} - T_{AG}) \quad (7)$$

106

107 The convective heat exchange coefficient  $h_c$  was determined from the correlation used by [29]:

$$h_{cv} = 1.31 \cdot |T_{CC} - T_{AG}|^{\frac{1}{3}} + 9 \quad (8)$$

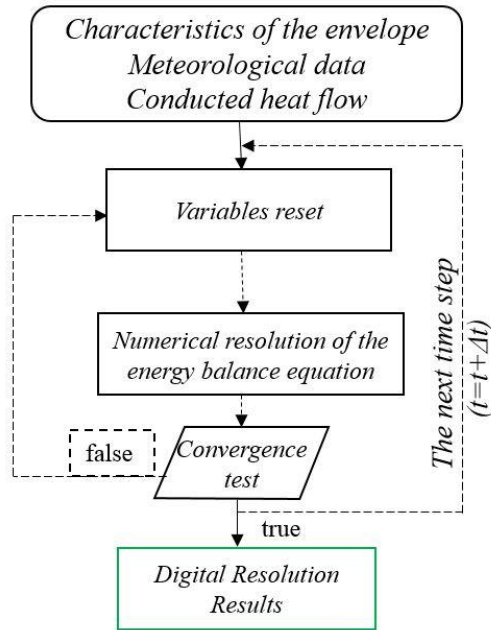
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109 The constant 9 of the last equation is an experimental factor recommended to take into account the effect of the  
 110 average wind speed.

#### 111 **2.3. Equations resolution**

112 The equations composing the energy balance at the outer surface of the cellular concrete wall (4), (6) and (8)  
 113 involve nonlinear terms according to the surface temperature of the cellular concrete wall ( $T_{cc}$ ).

114 A resolution of the energy balance equations was performed under Matlab using the Newton-Raphson method.  
 115 Thus, for each time step, the “theoretical” calculated temperature of the wall surface is evaluated numerically  
 116 with an iterative calculation. Once this temperature is approximated with an error deemed as acceptable, the  
 117 program resets the inputs to make the approximation in the next time step and so on, until the last time step  
 118 entered for the end of the calculations (Fig. 3).



119

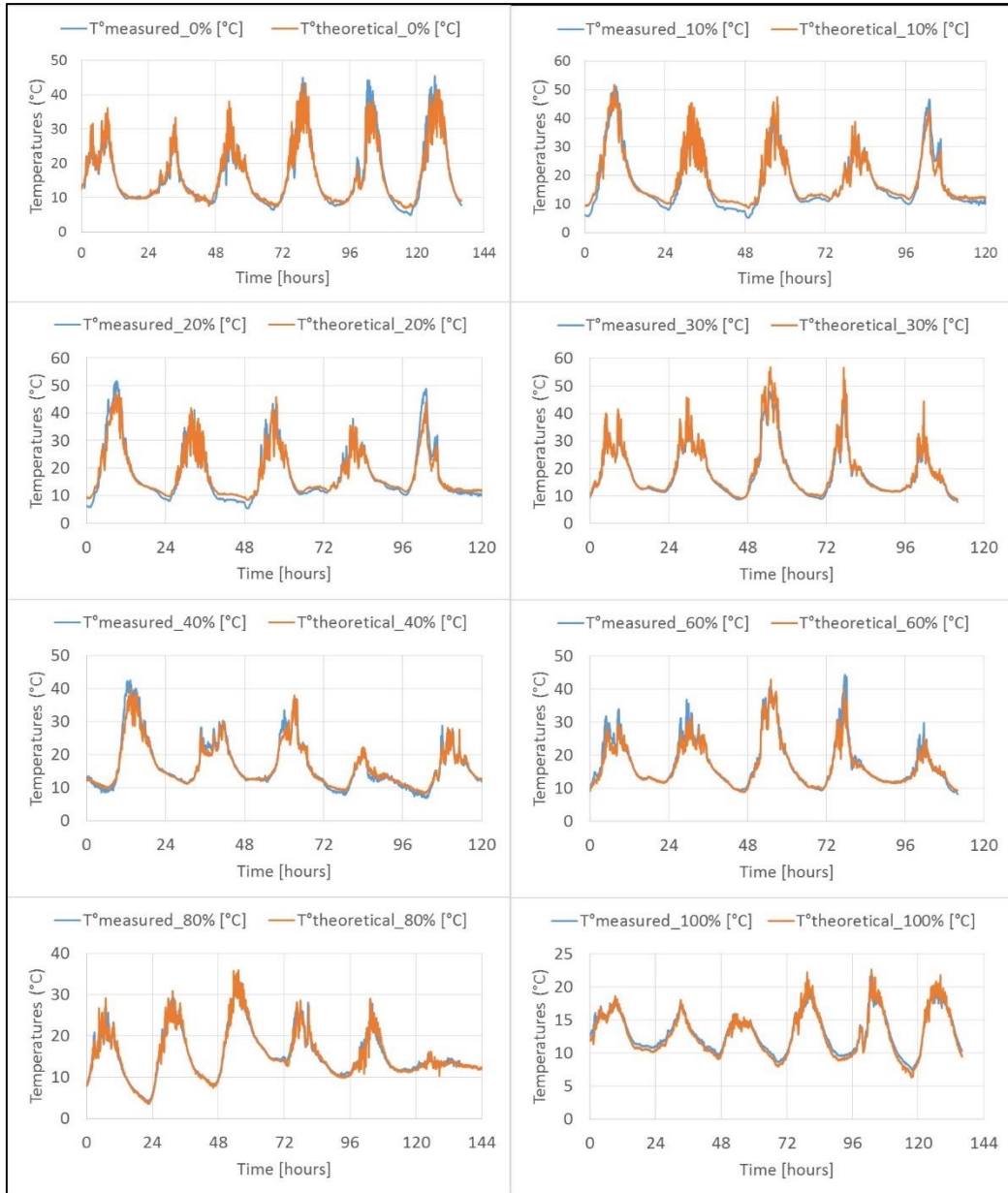
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**Fig. 3:** Diagram of the resolution algorithm.

121 For the operation of the algorithm (Fig. 3), it is necessary to introduce the characteristics of the envelope and the  
 122 meteorological data. The heat flux on the outer surface of the cellular concrete wall must also be provided at each  
 123 time step in order to evaluate the temperature. The temperatures evaluated with this algorithm are validated  
 124 experimentally in the following section.

125 **2.4. Preliminary model validation**

126 A comparison between the theoretical temperatures, represented in orange ( $T^{\circ}_{\text{theoretical}}$ ) and the measured  
 127 temperatures, in blue ( $T^{\circ}_{\text{measured}}$ ) was carried out for the different coverage rates (0-100%) in order to  
 128 validate the preliminary model based on the energy balance equations in the artificial occultation test (Fig. 4).



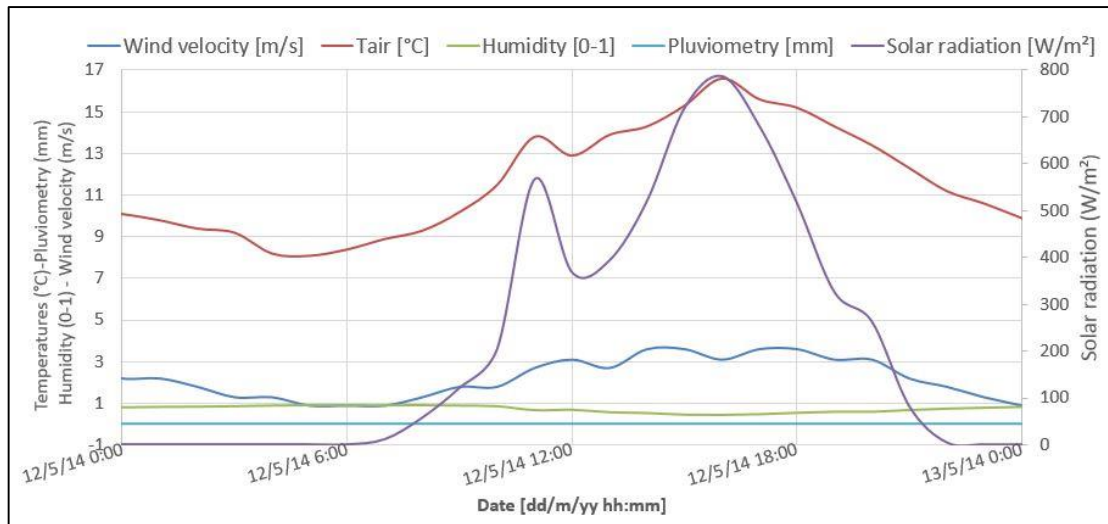
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130

**Fig. 4:** Comparison of numerical and experimental results.

131 For all coverage rates, the theoretical model closely reproduces the measured temperature. For example, in the  
 132 case of coverage rates of 100%, the mean deviation between the theoretical temperatures curve and the  
 133 experimental curve for a period of 6 days was 0.54 °C.

134 A typical day was selected to better illustrate the comparison between the numerical results and the experimental  
 135 results. The coverage rate during this typical day (12/05/2014) was 50% on the lab3, and the meteorological data  
 136 used for the chosen day are shown in Fig. 5.



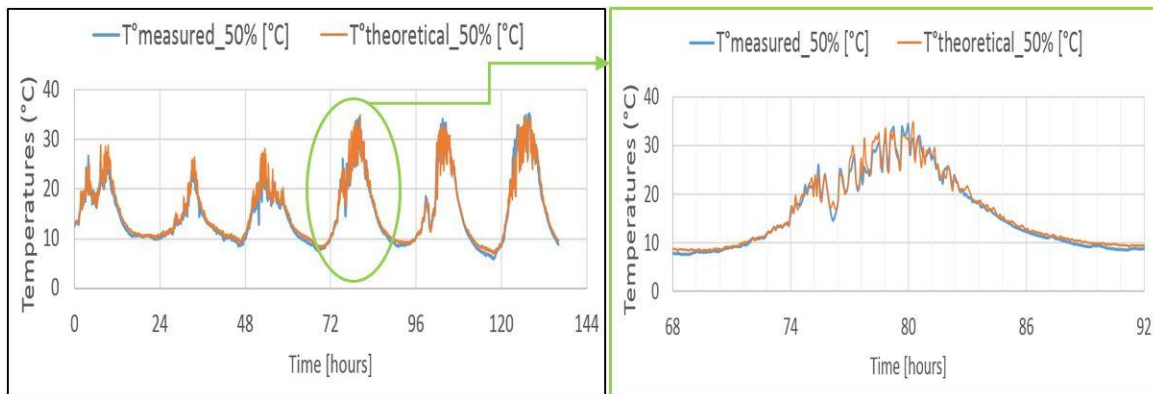
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138

**Fig. 5:** Meteorological data.

139 This typical day was selected according to the maximum temperature values and the solar radiation recorded  
 140 during the period of the test of the controlled occultation rate. The peak of solar radiation was 786 W/m<sup>2</sup> at  
 141 16h00, while the ambient air temperature was around a maximum of 16.6°C for the period and a minimum of  
 142 8.1°C recorded at 5h00. No precipitation was observed during this day, but high humidity values were recorded  
 143 during the night and in the morning (82% to 90% between 1h00 and 10h00). The wind speed was relatively low  
 144 during the selected sequence (0.9 to 3.6 m/s).

145 The results of validation of the theoretical model during the typical sequence are illustrated in Fig. 6.



146

**Fig. 6 :** Comparison between theoretical and measured temperatures ( $\sigma_{occ}=50\%$ ).

148 In this figure, it is observed that the calculated heat flux is globally similar to that which is measured. The mean  
 149 deviation between the theoretical and measured temperature is of the order of 1.3°C. Deviations of up to 3.8°C  
 150 were recorded during peaks and in the rapid changes in solar radiation. These deviations coincide with the period  
 151 when solar radiation is rapidly changing from 500 to 786 W/m<sup>2</sup>. During the night and in the morning, the  
 152 deviations are relatively higher than the mean values, they correspond perfectly to the sequence in which, the

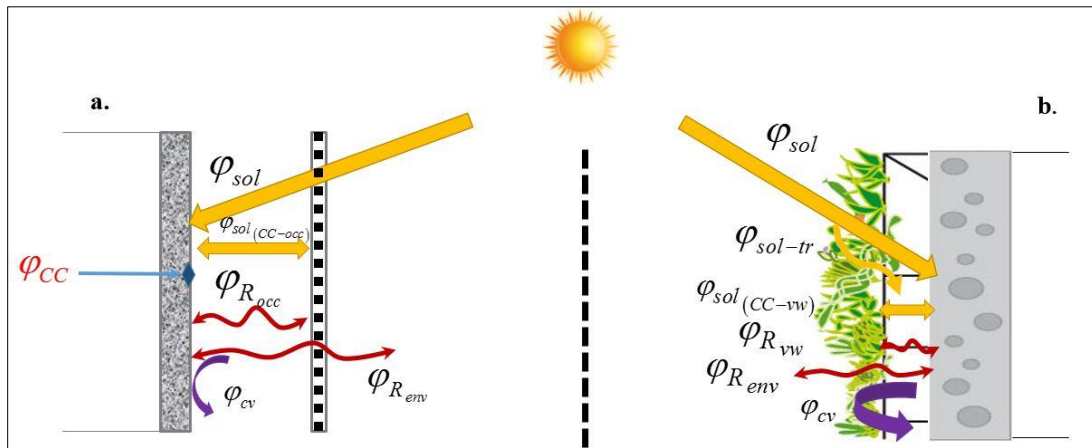
153 relative humidity was very high and the solar radiation not exceeding 200 W/m<sup>2</sup>.  
 154 Despite these few deviations corresponding to particular sequences (high humidity and rapid change of solar  
 155 radiation), the influence of the coverage rate was reproduced fairly accurately throughout the test.  
 156 The good similarity obtained, between the theoretical model and the experimental results, allowed an appropriate  
 157 validation of the controlled occultation model. The equations of this model will be used as a basis for the  
 158 modelling of the behaviour of the vegetalized walls.

159 **2.5. Adaptation of equations to the case of vegetation**

160 The energy balance at a wall obscured by vegetation is based on the balance equations of solar radiation  
 161 exchanges, infrared exchanges and convective exchanges (Equation 9).

162 
$$\varphi_{cc} = \varphi_{sol} - \varphi_{R_{env-CC}} - \varphi_{R_{vw-BC}} - \varphi_{cv} \quad (9)$$

163 Among the major differences between the two types of occultation is the semi-transparent foliage aspect of  
 164 plants. This involves a new equation quantifying the solar flux ( $\varphi_{sol-tr}$ ) which crosses the "vegetation cover"  
 165 and involves several and numerous parameters (only parameters related to the obscuration effect are treated)  
 166 (Fig. 7).



167 **Fig. 7:** Elements of the energy balance ;(a) case of artificial obscuration ; (b) case of masking by the vegetation.

168 The second important difference is related to the geometry of the occultation. In the experiment, realized with  
 169 artificial occultation, the objective was to master the role of the coverage rate. This has been possible by using a  
 170 relatively simple structure where each of the meshes of the occultation lies in the same plane and thus in two  
 171 dimensions (2D). In the case of vegetation, the leaves of the plants replace the square meshes. The distribution of  
 172 plant leaves is not limited by a 2D plan. The thickness of the leaf layer, the density and the number of leaves are  
 173 new parameters to be integrated into the energy balance equations. This last aspect requires modification of the

174 transmitted and absorbed solar radiation and an adaptation of the equations of convective exchanges. These  
 175 convective exchanges are considered in the case of the artificial occultation to be similar to exchanges between  
 176 two flat surfaces. They are more complex in the case of plants, and it is then necessary to take into account an  
 177 aerodynamic resistance in the external surface area of the leaf layer and a resistance to the sensible heat transfer  
 178 within the canopy layer, following its thickness, and the density of leaves.

### 179 **2.5.1. Radiative exchanges**

180 The radiative exchanges balance was adapted according to the characteristics of the plants, no change was made  
 181 to the infrared radiation equations between the cellular concrete wall ( $W_{CC}$ ) and the environment (Equation 10)  
 182 on one hand and between the VW and the  $W_{CC}$  on the other hand (Equation 11):

$$183 \quad \varphi_{R_{CC-env}} = \frac{\varepsilon_{BC} \sigma \times (T_{CC}^4 - T_{EQ}^4) \times (1 - \sigma_{vw})}{1 - \sigma_{vw} \times (1 - \varepsilon_{CC})} \quad (10)$$

$$184 \quad \varphi_{R_{vw-CC}} = \frac{\sigma \times (T_{CC}^4 - T_{vw}^4)}{\frac{1 - \varepsilon_{CC}}{\varepsilon_{CC}} + \frac{1}{\sigma_{vw}} + \frac{1 - \varepsilon_{vw}}{\varepsilon_{vw}} \times \frac{1}{\sigma_{vw}}} \quad (11)$$

185 Since the leaf layer of plants is considered semi-transparent to solar radiation, a transmitted flux term has been  
 186 added ( $\varphi_{sol-tr}$ ). This adds to the direct solar flux and to those exchanged between the masking and the  $W_{CC}$   
 187 have been expressed respectively by ( $\varphi_{sol}$ ) and ( $\varphi_{sol(vw-CC)}$ ) in equations (12, 13).

$$188 \quad \varphi_{sol} = \alpha_{CC} (1 - \sigma_{vw}) \times Is \quad (12)$$

$$189 \quad \varphi_{sol(vw-CC)} = Is^{\downarrow} \times \alpha_{CC} (1 - \sigma_{vw}) \times \sum_{n=2}^{\infty} r_{CC}^n (\sigma_{vw} \times r_{vw})^{n-1} \quad (13)$$

190 The radiative flux transmitted by the foliar layer of plants ( $\varphi_{sol-tr}$ ), is obtained as a function of the incident solar  
 191 radiation, the  $W_{CC}$  absorption coefficient, the coverage rate of the plant layer and the solar transmission  
 192 coefficient of the leaf layer (Equation 14).

$$193 \quad \varphi_{sol-tr} = Is^{\downarrow} \times \alpha_{CC} \times \sigma_{CC} \times \tau_{vw} \quad (14)$$

194 The foliar solar transmission coefficient  $\tau$ , is determined according to a simplified approach which consists in  
 195 assuming the foliar layer as a homogeneous medium in which the radiation is absorbed and not diffused. With  
 196 this assumption, the Beer-Lambert law can then describe the exponential attenuation of the radiation passing

197 through the leaf layer [23, 30]. Thus, the coefficient ( $\tau_{vw}$ ) is calculated as a function of the solar zenith angle  
 198 ( $\beta_{zen}$ ), the leaf coverage index ( $F$ ) and a solar extinction coefficient ( $\mu^*$ ) which vary according to the radiative  
 199 properties of the leaves and their mean inclination (Equation 15).

$$200 \quad \tau_{vw} = \exp(-\mu^* \times \beta_{zen} \times F) \quad (15)$$

201 The inclination of the leaves and the radiative properties of the plants ( $\mu^*$ ) determine the depth up to which  
 202 direct solar radiation (of  $\beta$  zenith angle) can penetrate in the leaf layer without being intercepted. The foliar cover  
 203 index ( $F$ ), for its part, is a dimensionless quantity, representing the spatial distribution of the leaf structure in  
 204 three dimensions. In other words, the index  $F$  is taken to be equal to the coverage rate in the case of a spatial  
 205 distribution in 2D only (case of artificial occultation). It is defined as the ratio between half of the total surface  
 206 area of the leaves (up and down seeds) and the total surface area (CC wall). Unlike the coverage rate, which is  
 207 limited to the ratio between the covered area and the total area, the index  $F$  is calculated taking into account the  
 208 total number of leaves, even if they are superimposed (Equation 16).

$$209 \quad F = \frac{1/2 \text{ Total leaf area}}{W_{cc} \text{ area}} \quad (16)$$

### 210 **2.5.2. Convective exchanges**

211 The new model of convective exchanges is inspired by the model validated by [23]. It is expressed as a function  
 212 of an aerodynamic resistance of the top layer of the plants ( $ra$ ) and a resistance to the sensible heat transfer ( $rc$ )  
 213 within the foliage. The introduction of the two "resistances" (in  $s.m^{-1}$ ) is similar to that which is generally used  
 214 for the modelling of heat transfer by electrical analogy. The new convective flux at the level of the leaf layer,  
 215 involving these two resistances, is given by the following equation:

$$216 \quad \varphi_c = \frac{\rho_{air} \times cp_{air}}{rc + ra} (T_{cc} - T_f) \quad (17)$$

217 The aerodynamic resistance ( $ra$ ) is defined by the variation of the wind speed above a rough surface. It is  
 218 determined according to a general model often used by climatologists to describe the wind velocity profile at the  
 219 upper boundary layer of a plant canopy [31, 32]. According to [23], the aerodynamic resistance ( $ra$ ) which takes  
 220 into account the very small deviations between the ambient air temperature and the foliage temperature can be  
 221 calculated by equation (18):

222 
$$ra = \frac{\left[ \ln \left( \frac{(z_U - d_0)}{z_{0m}} \right) \right] \times \left[ \ln \left( \frac{(z_U - d_0)}{z_{0H}} \right) \right]}{k^2 u_m} \quad (18)$$

223 With ( $k$ ) the Von Karman constant ( $k \approx 0.40$ ) and ( $u_m$ ) the wind speed measured at the distance ( $z_U$ ). Whereas,  
 224 the displacement height ( $d_0$ ) and the roughness lengths ( $z_{0H}$ ) and ( $z_{0m}$ ) are calculated, according to [33], as a  
 225 function of the height of the plant canopy ( $h_f$ ) :

226 
$$\begin{aligned} d_0 &= 0.701 h_f^{0.975} \\ z_{0m} &= 0.131 h_f^{0.997} \\ z_{0H} &= 0.1 z_{0m} \end{aligned} \quad (19)$$

227 The resistance to sensible heat transfer ( $rc$ ) intervenes inside the plant layer. It is determined as a function of the  
 228 velocity of the air flow within the plant canopy ( $uc$ ) using the relationship below [34–36]:

229 
$$rc = \frac{1}{0.004 + 0.012 uc} \quad (20)$$

230 The air flow velocity within the plant layer ( $uc$ ) is reduced as function of a specific coefficient of the vegetation  
 231 layer ( $a$ ) and is determined according to the following equation:

232 
$$uc = \left[ um \cdot \ln \left( \frac{(h_f - d_0)}{z_{0m}} \right) / \ln \left( \frac{(z_U - d_0)}{z_{0H}} \right) \right] \cdot e^{-a \left( 1 - \frac{0.05}{h_f} \right)} \quad (21)$$

233 The coefficient ( $a$ ) (in eq (21)) is calculated according to the foliar surface index ( $F$ ), the height of the plant  
 234 canopy ( $h_f$ ) and the average leaves thickness ( $df$ ):

235 
$$a = \sqrt{0.2F \cdot \frac{h_f}{df}} \quad (22)$$

236 Henceforth, the different equations used in the first part have been adapted to the case of vegetation. They will  
 237 be validated after the determination of the coverage rate by an image analysis method.

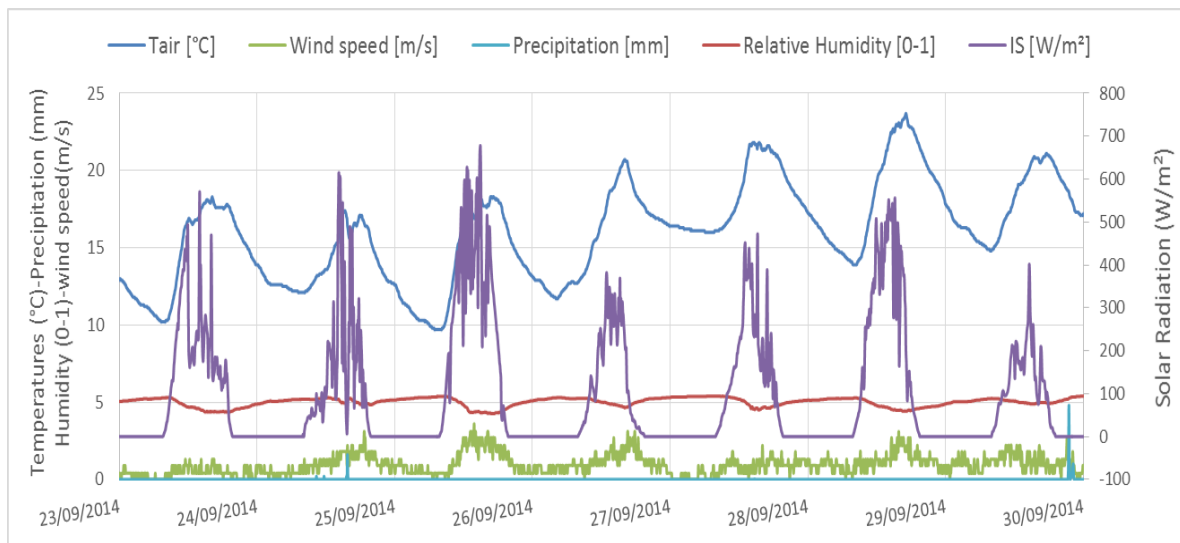
### 238 3. Experimental validation

239 The different equations having the wall surface temperature ( $T_{cc}$ ) as unknown parameter were solved with the  
 240 Newton Raphson method. Then, in order to verify the relevance of the theoretical model, the results of the  
 241 calculations were compared with the experimental measurements [27]. The parameters used in the theoretical  
 242 modelling are grouped in table 1.

**Table 1:** Parameters for experimental validation

Parameters	Value	Parameters	Value
$\alpha_{CC}$	0.90	$\varepsilon_{CC}$	0.96
$\sigma_{vw}$	0.45	$\sigma$	$5.67 \cdot 10^{-8}$
$r_{CC}$	0.1	$\varepsilon_{vw}$	0.95
$r_{vw}$	0.3	$h_f$	0.15
$\mu^*$	0.75	$d_f$	0.001
$F$	3		

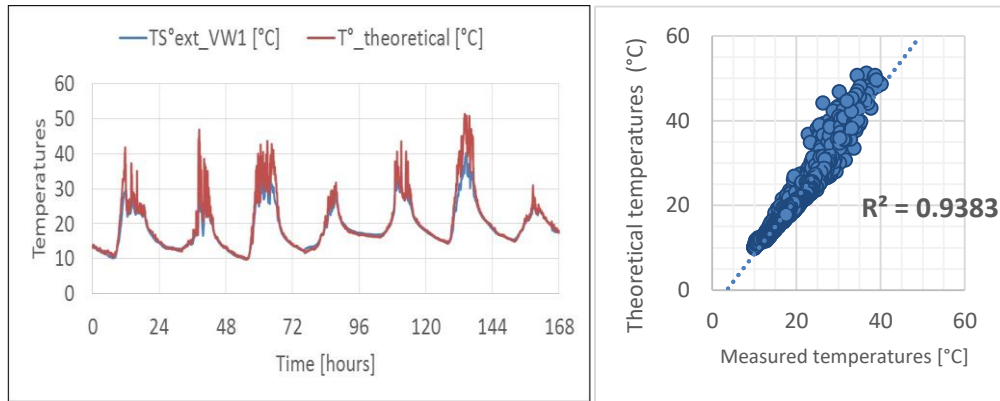
244 The experimental data used for validation were recorded by the mini thermal lab at the end of the summer period  
 245 of 2014. The meteorological data entered as inputs to the program are: ambient air temperature, short-wave solar  
 246 radiation, equivalent environmental temperature and wind speed. In addition, data on precipitation and relative  
 247 humidity are given only for information. These additional data may be useful for understanding numerical  
 248 prediction errors, which generally coincide with possible rapid changes in the values for these two parameters  
 249 (Fig. 8).



250 **Fig. 8:** Meteorological data of the validation sequence

251 During the sequence selected for experimental validation, the air temperature varied between 9 and 24°C. While  
 252 the wind speed never exceeded 3.6 m/s over the entire validation sequence. As for solar radiation, the maximum  
 253 values ranged between 400 and 700 W/m<sup>2</sup> with very rapid oscillations during the first three days of validation  
 254 because of frequent cloud crossings.

255 The theoretical temperatures obtained for the surface of the CC wall were then compared with the outside  
 256 surface temperatures recorded by the "Lab 2" (Fig. 9).



257 **Fig. 9:** Comparison of theoretical and measured temperatures

258 From the comparison, it appears that the numerical prediction is generally very close to the experimental values.  
 259 The temperatures from the numerical calculations correspond to the experimental temperatures within about  
 260 1.5°C.

261 The average deviation observed corresponds to an average error of  $\pm 6.4\%$  throughout the validation sequence.  
 262 However, it should be noted that the differences between the calculated and the measured temperatures are less  
 263 than 1°C over 90% of the values. The error calculated on 90% of the values, which does not take into account the  
 264 deviations due to the rapid variations of the solar radiation, is less than 4.7% (less than 1°C). This difference is  
 265 very acceptable for validations under external conditions.

266 **4. Conclusion**

267 This work presents a new contribution to the numerical evaluation of the thermal effects of vegetalized walls. A  
 268 preliminary theoretical model was established at the end of the experimental part and the overall heat flow  
 269 behaviour under the imposed coverage rates was reproduced very correctly. The comparison between theoretical  
 270 and experimental temperatures allowed the validation of the proposed model on small scale. The model will be  
 271 improved and better adapted to the case of climbing plants and then integrated into a thermal building simulation  
 272 software. This will enable the prediction of the effect of plants on the thermal behaviour of a real building under  
 273 various climates. The modelling of the effects of the occultation by a vegetable screen was introduced by  
 274 presenting the differences between a vegetable screen and the occultation by an artificial material. New  
 275 equations incorporating these modifications have been added to the model established in the first part. Then, the  
 276 results from the new model were compared with the experimental results. The relevance of the numerical model  
 277 has been discussed through experimental confrontation.

278 The experimental and theoretical approaches undertaken, demonstrated the thermal interest of simple vegetalized  
 279 walls and highlighted the complexity of the transfer phenomena within a plant layer. This will allow future

280 modelling of the thermal effect of plants on buildings at real scale. The developed digital tool made it possible to  
281 bring more precision on the effects of plants in regions with a temperate climate. It will also allow the study of  
282 the thermal effects of simple vegetalized walls in other climates and for different constructions.

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