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33 I. Introduction

34 Global warming coupled with continuous increase in building energy consumption
35 has set off the international alarm. Over and above that, an additional growth by about 40%
36 in building energy usage is estimated to occur in the next 20 years due to increasing demand
37 for thermal comfort (Mariano-Hernández et al.) Therefore, the adoption of sustainable,
38 energy saving and eco-friendly technologies in the building sector based on low cost bio-
39 based materials has become an emergency response plan worldwide. Subsequently 75,000
40 tons of fossil fuels are likely to be saved in France in 2050 while avoiding the rejection of
41 312,771 tCO₂eq due to an energy recovery from bio-based insulation wastes (Rabbat et
42 al.2022).

43 The continuous population and economy growth has led to an exponential increase in global
44 energy demand with more than 80% of the current primary energy consumed is produced
45 from fossil fuels that is likely to be depleted in the next century (Yoon et al.2010). Finding
46 alternative low cost clean energy sources represents an important challenge.

47 Building energy consumption currently accounts for over 40% of the total primary energy
48 consumption in the U.S. and E.U. (Cao et al.2016). In France, it is classified as the most
49 energy- consuming sector, which accounts for 43% of the total energy consumption and as
50 the second most contributor to CO₂ gas emissions with a total contribution of 25%, just after
51 the transportation sector (ADEME, 2013). Therefore, achieving a reduction in the total
52 building energy consumption can provide key solutions to reduce energy demand and
53 carbon emissions, which are considered as a serious threat to our societies.

54 Nevertheless, providing thermal comfort in buildings takes a major proportion of the total
55 building energy consumption. Thus, enhancing the thermal insulation of building envelopes
56 can significantly decrease building energy consumption. In this regard, insulation materials
57 with a lower thermal conductivity will furtherly reduce heat flow crossing a building
58 envelope which is responsible for 50-60% of total heat transfer in a building (Kumar et
59 al.2020).

60 Therefore, optimization of thermal insulation for building envelope is crucial for thermal
61 comfort, energy saving and reducing greenhouse gas emissions. While conventional building
62 insulation materials are largely based on non-renewable resources requiring high

63 manufacturing energy, alternative sustainable insulation materials based on agro residues
64 have been identified as low-embodied energy materials that simultaneously reduces energy
65 demand and reinforces decarbonisation of the building sector.

66 Recently, many studies have been conducted on the mechanical, hygrothermal and
67 acoustical performances of low-cost bio-based products for building insulation with
68 promising results. In This regard, Badouard & coll. (2021) investigated the development and
69 characterization of new bio-based materials based on viticulture by-products and potato
70 starch for building insulation use. For this matter, four types of aggregates (grape pomace,
71 stalks, skins, and crushed stalks) were used and mixed separately with potato starch. The
72 starch/aggregate mass ratio was set at 20% for all mixtures and four types of composites
73 were obtained and studied in terms of density, thermal conductivity, mechanical properties
74 and sound absorption coefficient. Bourdot & coll. (2017) studied physical, mechanical and
75 hygrothermal properties of a bio-composite made solely from wheat starch and hemp
76 shives. The influence of hemp shive size and hemp/ wheat starch ratio on were investigated
77 through an experimental approach. Mao & coll. (2017) studied hygrothermal properties of
78 bio-insulation building materials based on bamboo fibers and bio-glues made up from bone
79 glue mixed with sodium lignosulfonate. Bakatovich & coll. (2022) investigated the thermal
80 insulation of materials based on reed and straw fibres bonded with sodium silicate and
81 rosin. Bovo & coll. (2022) investigated thermal and acoustical performance of corncob for
82 building insulation applications. Maalouf & coll. (2014) studied the hygrothermal behaviour
83 of a hemp concrete building envelope under summer conditions in three French teams.
84 Collet & coll. (2014) studied the impact of formulation, density and water content on the
85 thermal performance of hemp concrete and observed a higher increase of the thermal
86 conductivity with increasing density of hemp concrete in comparison with increasing water
87 content, which had a lower effect. Colinart & coll. (2016) analysed the transient
88 hygrothermal behaviour of a multi-layered hemp concrete wall coated with interior and
89 exterior coarse plasters made of lime–sand mixtures. Other research works have focused on
90 reinforcing mineral fibres with vegetal fibres in order to obtain a bio-composite, the main
91 goal of this process being to benefit from the physical properties of the vegetal fibres and
92 the mechanical properties of the mineral binder. Haba & coll. (2017) investigated the
93 hygrothermal effect of a bio-composite insulation material for building application based on
94 date palm concrete. Aouba & coll. (2015) studied the influence of incorporating wheat

95 straw to fired clay bricks on the thermal conductivity with reference to the bulk density,
96 porosity and brick geometry. Hou & coll. (2017) showed that filling hollow concrete blocks
97 with compressed straw reduces heat transfer and improve moisture-buffering performance.

98 In this regard, the sugar extraction process from sugar beets produces beet pulp that
99 is considered as a low cost by- or waste product. Furthermore, the beet pulp production is
100 continuously increasing with millions of tons of beet pulp pellets being produced yearly in
101 France and Europe. Therefore, this low cost bio-based and locally available product
102 happened to be an interesting substrate to be investigated for building insulation use.

103 Subsequently, various studies investigated a new bio-composite material based on sugar
104 beet pulp and potato starch for building insulation use on material scale level. During his
105 PhD studies, Karaky (2018) studied physical properties (morphology, porosity, density and
106 particles size) of sugar beet pulp in addition to hygrothermal, mechanical and acoustical
107 performances of different bricks made of different starch-beet pulp (S/BP) mass ratio (S/BP
108 = 0.1, 0.2, 0.3 and 0.4.). The results showed that for an increase of the S/BP mass ratio, the
109 thermal conductivity, mechanical properties, density and moisture buffering value increased
110 and that the porosity and sound absorption coefficient of this bio-composite decreased. In
111 this matter, a 0.4 mass ratio was found to be the optimal composition of S/BP in terms of
112 the hygrothermal and mechanical properties and whereas a thermal conductivity at dry
113 state was found equal to 0.075 (W/m. K) (Karaky et al. (2018); Karaky et al. (2019)).
114 Moreover, Costantine and coll. (2020) compared the drying kinetics and mechanical
115 properties of whole vs. hollowed bricks both having similar mixture composition of S/BP
116 with a 40 % mass ratio compacted under a pressure equal to 0.044 MPa. The results showed
117 that hollowed bricks had a more homogeneous and faster drying kinetics, higher elasticity
118 modulus and compression resistance compared to whole bricks, showing that hollowed
119 S/BP bricks can be used as a rigid material for building application.

120 The hollow block's structural configuration highly influenced the thermal characteristics and
121 whereas Zhang & coll. (2017) studied the impact of rib width, number of rows with holes,
122 number of holes, hole thickness and arrangement. The results showed that the thermal
123 performance of the hollowed block with identical dimensions improved with the increase of
124 number of rows with holes having a diameter not larger than 0.02 m.

125 For this reason and in order to study the optimal thermal performance of hollowed S/BP
126 bricks with a constant mass ratio equal to 40%, numerical studies on thermal resistance
127 using COMSOL v. 5.6 software were conducted on different hollowed bricks configurations.
128 The results are then compared with analytical calculations based on the NF EN ISO norm
129 6946. (2017) and an optimal holes configuration in terms of thermal and mechanical
130 performance was deduced. Afterwards, two experimental studies on the thermal
131 performance were carried out on a 1m x 1m wall made of hollowed S/BP bricks cemented
132 together by a 1cm layer of S/BP identical mix. The wall was inserted in a bi-climatic chamber
133 THERMO³ in order to measure its thermal resistance(3R, n.d.). Afterwards, highly precise
134 thermal images were recorded by using the varioCAM HD (JENOPTIK, n.d.). For this matter,
135 the S/BP wall was fixed from one side to the hot climatic chamber and exposed from the
136 other side to ambient temperature, and heat transfer through the wall was analyzed by
137 thermal imaging.

138 **II. Numerical study**

139 **II.1 2D-numerical simulations of bricks**

140 Hollow blocks are widely used in construction for having lighter weight and better insulation
141 properties against heat and dampness. In order to achieve a better thermal performance of
142 the S/BP bricks, a numerical study on holes distribution was conducted using the
143 commercial software COMSOL v. 5.6.

144 The numerical simulations were set-up as a 2D simulation using the heat transfer in fluids
145 and the surface-to-surface radiation physics interfaces and the built-in properties of air in
146 the software COMSOL were used. Even though in a real façade the heat fluxes might be 3D
147 in nature, a 2D simulation here was considered sufficiently accurate because the simulations
148 were done on the level of one brick and the cross section of the brick is constant over its
149 height.

150 The S/BP mixture was included as a solid (non-transparent for IR radiation), the air as a fluid
151 (transparent for IR radiation; not including fluid flow; using the built-in properties of air) and
152 the boundaries of the holes as diffuse surfaces with emissivity of 0.9 in order to exchange IR
153 radiation through the holes. The governing equations for the heat transfer through the
154 solids/fluids were defined by Eq. (1) and Eq. (2):

$$\nabla \cdot q = 0 \quad (1)$$

$$q = -\lambda \nabla T \quad (2)$$

155

156 With q (W/m^2) the heat flux density vector, λ ($\text{W}/\text{m}\cdot\text{K}$) the thermal conductivity and T (K)
 157 the temperature.

158 The surface-to-surface radiation heat transfer through the air-filled holes was governed by
 159 Eq. (3) to Eq. (8):

$$J = \varepsilon e_b(T) + \rho_d G \quad (3)$$

$$\varepsilon + \rho_d = 1 \quad (4)$$

$$G = G_m(J) + G_{amb} \quad (5)$$

$$G_{amb} = F_{amb} \varepsilon_{amb} e_b(T_{amb}) \quad (6)$$

$$e_b(T) = n^2 \sigma T^4 \text{ with } n = 1 \quad (7)$$

$$q_{r,net} = \varepsilon(G - e_b(T)) \quad (8)$$

160 with J (W/m^2) the surface radiosity, ε (-) the surface emissivity, $e_b(T)$ (W/m^2) the blackbody
 161 total emissive power, ρ_d (-) the surface reflectivity, G (W/m^2) the surface irradiation, $G_m(J)$
 162 (W/m^2) the mutual surface irradiation, G_{amb} (W/m^2) the ambient irradiation, F_{amb} (-) the
 163 ambient view factor, ε_{amb} (-) the ambient surface emissivity, n (-) the transparent media
 164 refractive index, σ ($\text{W}/(\text{m}^2\cdot\text{K}^4)$) the Stefan-Boltzmann constant, $q_{r,net}$ (W/m^2) the net
 165 radiative heat flux density.

166 The boundary condition on the warm side of the brick was a heat flux boundary with a
 167 temperature of 20°C and surface heat transfer coefficient equal to $7.8 \text{ W}/\text{m}^2\cdot\text{K}$ while the
 168 boundary on the cold side was a heat flux boundary with a temperature of 0°C and surface
 169 heat transfer coefficient equal to $25 \text{ W}/\text{m}^2\cdot\text{K}$. The equations governing the heat flux
 170 boundaries were defined by Eq. (9) and Eq. (10):

$$-n \cdot q = q_0 \quad (9)$$

$$q_0 = h(T_{ext} - T) \quad (10)$$

171 With \mathbf{n} the normal vector, q_0 (W/m^2) the heat flux density on the surface, h ($\text{W}/\text{m}^2\cdot\text{K}$) the
172 surface heat transfer coefficient, T_{ext} (K) the temperature of the surrounding air and T (K) the
173 temperature of the surface.

174 The mesh was a physics-controlled mesh with ‘finer’ mesh size as defined in the COMSOL
175 software (see figure 1). This resulted in a total of 7498 triangular mesh elements.

176

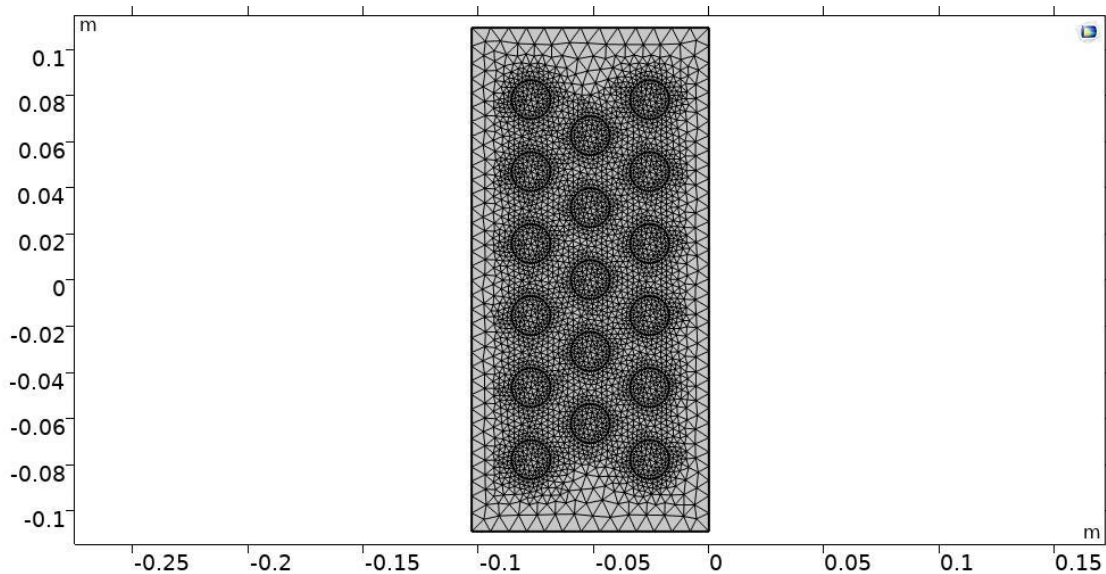


Figure. 1. Physics-controlled mesh for “finer” mesh size in COMSOL of the design for $i=3$ and $j=6$

177 The thermal conductivity of S/BP composite was measured experimentally using ISOMET
178 2114 Applied Precision (APPLIED PRECISION, n.d.). For this matter, an electrical resistor
179 generating a defined heat flow was inserted in direct contact into the studied sample and
180 temperature measurements were taken periodically.

181 Four cubical samples ($10 \times 10 \times 10 \text{ cm}^3$) of the S/BP composite were elaborated with the same
182 manufacturing process of the bricks used in this study. Before measurements, samples were
183 dried using a climatic chamber MKF 720 Binder (BINDER, n.d.) at $50 \text{ }^\circ\text{C}$ and 10% RH then
184 cooled at $23 \text{ }^\circ\text{C}$ and 50 % RH for two weeks until stabilization. Afterwards, each sample was
185 tested alone and covered during the test in order to avoid humidity variation. An average
186 thermal conductivity equal to $0.09 \text{ W}/\text{m}\cdot\text{K}$ was obtained and used in our study.

187 The density and specific heat of the S/BP mixture were set equal to $360 \text{ kg}/\text{m}^3$ and 1450
188 $\text{J}/\text{kg}\cdot\text{K}$ respectively as previously measured (Karaky 2018).

189 With respect to the above mentioned conditions, 15 different simulations, each with a
 190 different holes configuration were run on a S/BP hollowed bricks with fixed dimensions (L =
 191 21.85 cm, w = 10.3 cm and h = 5.6 cm) and equal holes diameters (D=1.7 cm) filled with air.
 192 The thermal resistance and equivalent thermal conductivity of the entire brick was deduced
 193 from each simulation.

194 While “i” refers to the number of rows with holes and “j” refers to the number of holes in a
 195 row and for “i” greater than 1, the configuration j/j-1 represents that the first row contains
 196 “j” holes while the second row contains “j-1” holes and the configuration is repeated for the
 197 following rows as shown in table 1.

198 For a configuration i=3 and J=6, a schematic representation of a hollowed brick is shown in
 199 Fig. 2.

200 **Table 1**
 201 Total number of holes for different holes configuration.

i \ j/j-1	0/0	2/1	4/3	6/5	8/7
1	0	2	4	6	8
3	0	5	11	17	23
5	0	8	18	28	38

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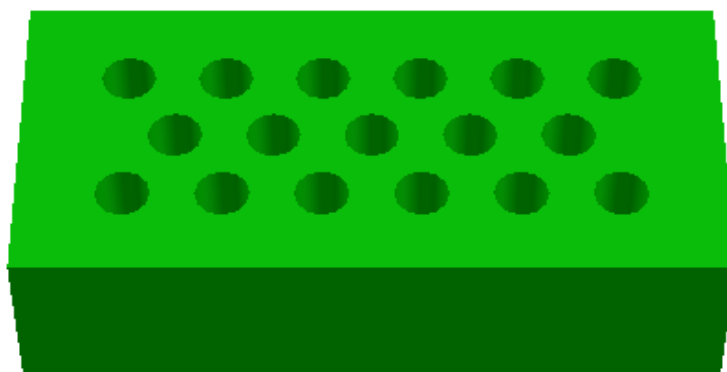


Figure. 2. Hollow brick design for i=3 and j=6

204 **II.1.1 Thermal performance under steady state**

205 Table 2 and 3 show the equivalent thermal conductivity and thermal resistance of S/BP brick
 206 for each hole configuration respectively. Fig. 3 and Fig. 4 show the impact of the total

207 number of holes on the equivalent thermal resistance and thermal conductivity respectively.
 208 The results show that the thermal resistance of the S/BP brick increases with increasing
 209 number of holes in a row and with the number of rows with holes. This can be explained by
 210 the fact that the brick in that case contains more air with a lower effective thermal
 211 conductivity than that of S/BP. The equivalent thermal conductivity of the brick equals 0.09
 212 W/m.K if holes are absent; this corresponds to the thermal conductivity of S/BP. For our
 213 study and in order to meet all the requirements described above, a configuration with 17
 214 holes was chosen for $i=1$ and $j=6$ and an equivalent thermal conductivity and thermal
 215 resistance were obtained respectively equal to 0.0873 W/m.K and $1.180 \text{ m}^2.\text{K}/\text{W}$.

216 **Table 2**

217 Equivalent thermal conductivity (W/m.K) of S/BP brick for different holes configuration.
 218

$i \backslash j/j-1$	0/0	1/2	3/4	5/6	7/8
1	0.0900	0.0897	0.0894	0.0890	0.0887
3	0.0900	0.0892	0.0883	0.0873	0.0864
5	0.0900	0.0887	0.0872	0.0856	0.0841

219

220 **Table 3**

221 Equivalent thermal resistance ($\text{m}^2.\text{K}/\text{W}$) of S/BP brick for different holes configurations
 222
 223
 224

$i \backslash j/j-1$	0/0	1/2	3/4	5/6	7/8
1	1.144	1.149	1.153	1.157	1.161
3	1.144	1.155	1.167	1.180	1.193
5	1.144	1.161	1.182	1.203	1.225

225

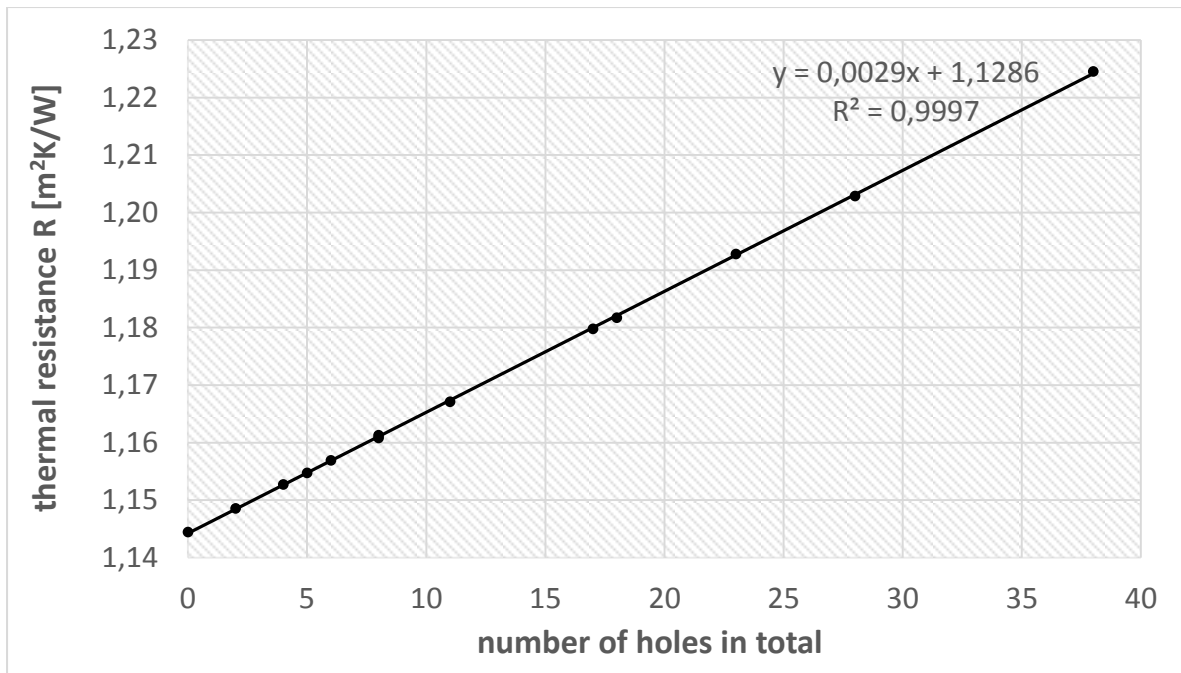


Figure. 3. Impact of holes number in a S/BP brick on the equivalent thermal resistance

226

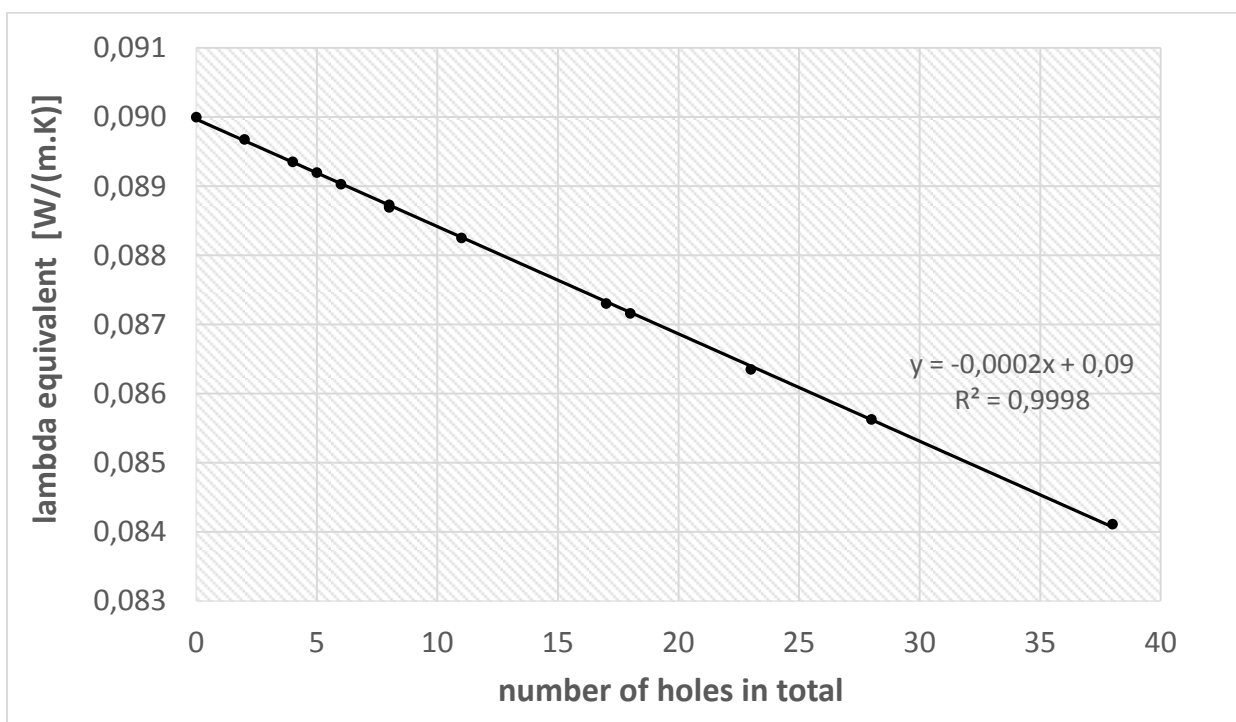


Figure. 4. Impact of holes number in a S/BP brick on the equivalent thermal conductivity

227

II.2 Analytical calculations

228

According to the NF EN ISO 6946 (2017), the thermal performance calculation of a hollowed construction component consisting of thermally homogenous and heterogeneous layers can be carried out while referring to the simplified calculation method. The thermal

229

231 resistance of each homogenous and heterogeneous part of the building wall is determined
 232 and then associated all together in order to obtain the equivalent thermal resistance of the
 233 wall and its equivalent thermal transmittance. To obtain the equivalent thermal resistance,
 234 a perforated S/BP brick was simplified as a 2D model as shown in Fig. 5. We proceeded by
 235 calculating the thermal resistance of a cylindrical hole in a first step, and then the thermal
 236 resistance of the S/BP composite based on the norm mentioned above from which the
 237 equivalent thermal resistance of a whole brick was concluded.

238

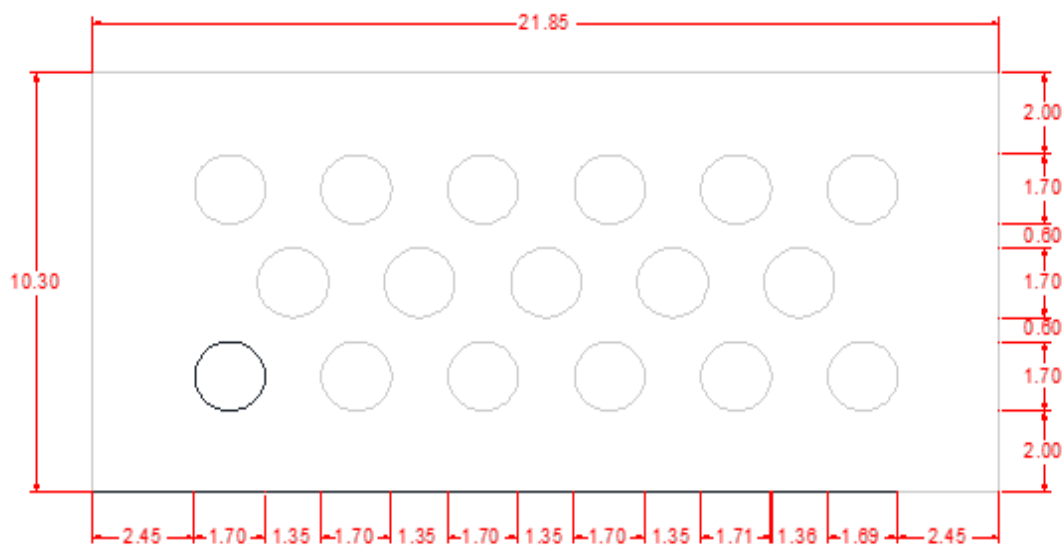


Figure. 5. S/BP brick dimensions

239 II.2.1 Thermal resistance of a cylindrical hole

240 According to the NF EN ISO 6946 (2017), air spaces with a thickness up to 0.3 m can
 241 be considered as thermally homogeneous. For a small air space having its width less than 10
 242 times its thickness and for a thickness that does not exceed 0.05 m and for the air space not
 243 exchanging air with the interior environment, the thermal resistance for this air space can be
 244 obtained by Eq. (11) to Eq. (15):

$$Ra_{x,y} = \frac{1}{ha_{x,y} + hr_{x,y}} \quad (11)$$

$$\Delta T_{hole_{x,y}} = Th_{hole_x} - Tc_{hole_y} \quad (12)$$

$$\Delta T_{average\ hole_{x,y}} = \frac{T_{hole_x} + T_{hole_y}}{2} \quad (13)$$

$$ha_1 = 1.25 \quad \text{if } \Delta T_{hole} < 5K$$

$$ha_2 = 0.73 \Delta T_{hole}/3 \quad \text{if } \Delta T_{hole} > 5K$$

$$ha_3 = \frac{0.025}{dx,y}$$

$$ha_{x,y} = \text{maximum value of } (ha_1, ha_2, ha_3) \quad (14)$$

$$\text{and } hr_{x,y} = \frac{4\sigma (\Delta T_{average\ hole_{x,y}})^3}{\frac{1}{\varepsilon_x} + \frac{1}{\varepsilon_y} - 2 + \frac{2}{1 - \frac{dx_y}{b_{xy}} + \sqrt{1 + \left(\frac{dx_y}{b_{xy}}\right)^2}}} \quad (15)$$

245

246 Moreover, it is assumed that the surfaces enclosing the air space are considered to have
247 high hemispherical emissivity in all directions equal to 0.9; therefore $\varepsilon_x = \varepsilon_y = 0.9$.

248 Table 4 shows the thermophysical properties of dry air at atmospheric pressure and $T =$
249 283.15 K. The thermal conductivity of the S/BP mixture was set equal to 0.09 W/m.K and as
250 for density and specific heat of the composite, values were set at 360 kg/m³ and 1450
251 J/kg.K respectively as found in the PHD thesis of Karaky. (2018) for a ratio of S/BP equal to
252 0.4.

253 **Table 4**

254 Thermophysical properties of dry air at atmospheric pressure and $T = 283.15$ K

255

ρ (kg/m ³)	C_p (j/kg.k)	λ (w/m.k)	μ (kg/m ² .s)	ν (m ² /s)	β (K ⁻¹)	Pr	α (m ² /s)	Reference
1.246	1006	0.02439	1.778E-05	1.426E-05	0.0035	0.7336	1.944E-05	Cengel & Ghajar (2020)

256

257 In order to simplify the geometry of the uniform cylindrical cavities for the heat transfer
258 calculation, having each a diameter of 1.7 cm and a height of 5.6 cm, an equivalent
259 thickness of the cylindrical cavities was used as shown in Fig. 6, and a simplified geometrical
260 scheme for the air cavity and the S/BP brick were adopted, as shown in Fig. 7 and Fig. 8.
261 respectively (Kočí et al. 2015).

262 Where T_1 and T_2 are the average surface temperatures of (T_1', T_1'') and (T_2', T_2'')
 263 respectively, D is the hole diameter and L is the equivalent length which represents the
 264 dimension of the air cavity in the direction of the heat flux which is obtained by Eq. (16):

$$L = 0.785 D \tag{16}$$

265

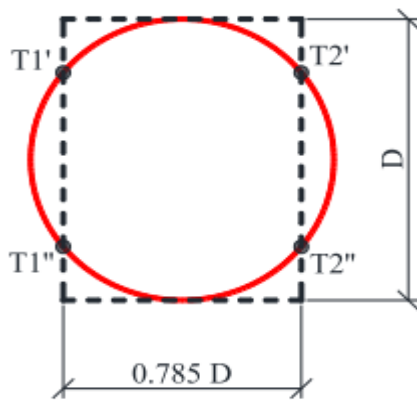


Figure. 6. Determination of the equivalent thickness of a cylindrical cavity

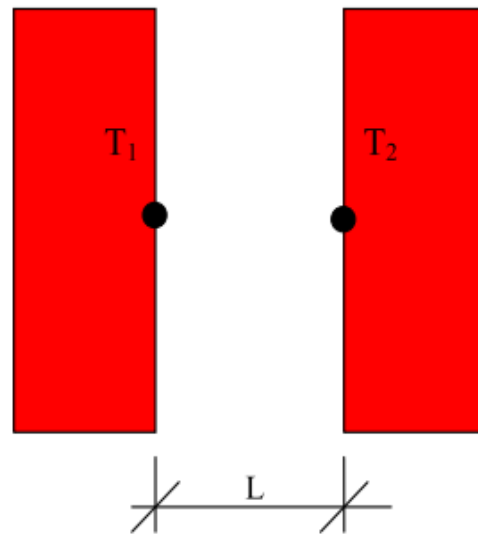


Figure. 7. Simplified scheme of the air cavity

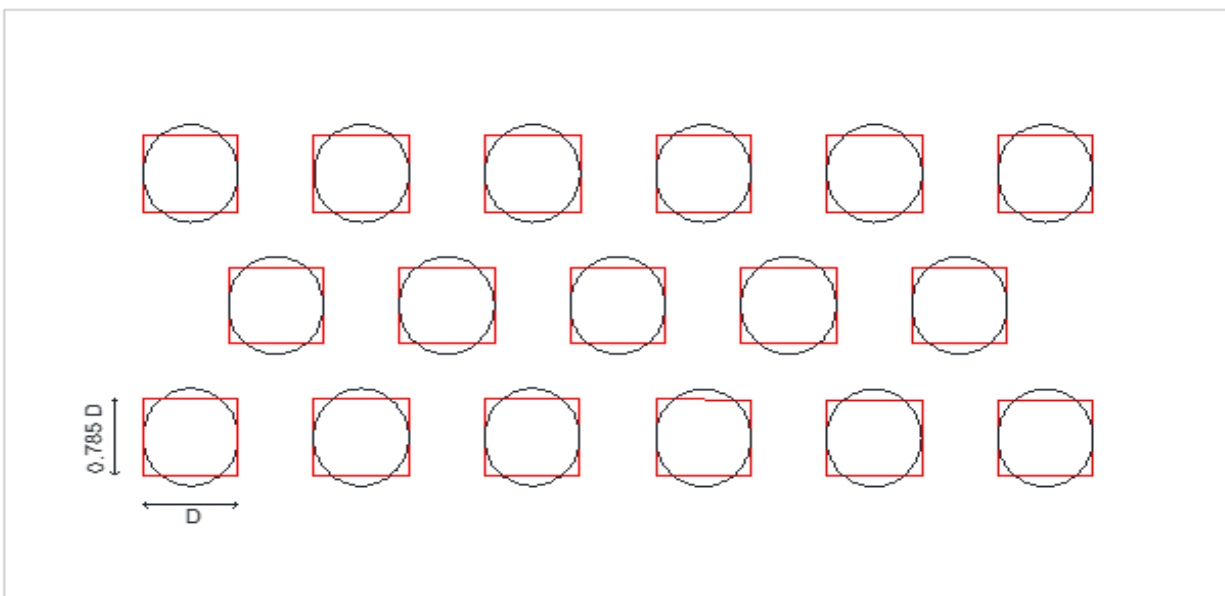


Figure. 8. Equivalent simplified scheme of S/BP brick

266 **II.2.2 Thermal resistance of the S/BP composite**

267 The microstructure analysis of the S/BP bio-composite mixture was done by
268 Costantine and coll. (2020) using scanning electron microscope (SEM) imaging. The results
269 showed that S/BP bio-composite had a rugged and open structure and the starch granules
270 were no longer visible and a good compatibility was seen between the two polymeric
271 constituents. Moreover, Karaky & coll. (2018) studied the porosity of the S/BP bio-composite
272 based on the cyclohexane insertion method while using a pycnometer and a porosity equal
273 to 70.6% was found for a S/BP ratio of 0.4. It is shown that the body itself is porous, but the
274 dimensions of the pore are so small that radiation and convection inside these pores can be
275 neglected thus it is considered that heat transfer occurs only through conduction (Kočí and
276 coll. (2015).

277 The thermal resistance of this bio-composite can be obtained by Eq. (17):

$$R_{x,y} = \frac{e_{x,y}}{\lambda m} \quad (17)$$

278 Where $R_{x,y}$ is the thermal resistance of the S/BP brick between points x and y ($m^2 \cdot K/W$),
279 $e_{x,y}$ is the thickness of the S/BP brick limited by points x and y (m) and λm is the thermal
280 conductivity of the S/BP bio-composite ($W/m \cdot K$).

281 **II.2.3 Heat flux calculation**

282 Assuming a unidimensional (1D) heat transfer, the total heat flux through the brick is
283 equal to the sum of the heat fluxes through each section of the brick, which is divided into
284 23 sections depending on its geometry and holes distribution as shown in Fig. 9.

285 The heat flux through each section is assumed to be constant from the bottom to the top of
286 the brick sections. Therefore, the total heat flux ΦT through the S/BP brick can be calculated
287 as follows by using Eq. (18) to Eq. (24):

$$\Phi T = \sum_{i=1}^{23} \Phi_i, S_i \quad (18)$$

$$\Phi_i = \frac{T_i - T_e}{R_i} \quad (19)$$

$$R_i = R_{s,i} + \sum R_{x,y} + \sum R_{a,x,y} + R_{s,e} \quad (20)$$

$$R_{s,i} = \frac{1}{h_i} \quad (21)$$

$$R_{s,e} = \frac{1}{h_e} \quad (22)$$

$$\Phi_i, S_i = \Phi_i \times S_i \quad (23)$$

$$\Phi T = 2 \times \Phi_{1,S1} + 2 \times \Phi_{2,S2} + 10 \times \Phi_{3,S3} + 5 \times \Phi_{4,S4} + 4 \times \Phi_{2',S2'} \quad (24)$$

288 Whereas, ΦT is the total unidirectional heat flux (W) crossing the total surface ST (m^2) of
 289 the S/BP brick and Φ_i, S_i is the heat flux density Φ_i crossing through the section S_i of the
 290 brick having R_i as an equivalent thermal resistance ($m^2.K/W$), as shown in Fig. 9.

291 T_i , T_e , $R_{s,i}$, $R_{s,e}$, h_i and h_e are respectively the internal temperature (K), the external
 292 temperature (K), the inner surface thermal resistance due to convection ($m^2.K/W$), the outer
 293 surface thermal resistance due to convection ($m^2.K/W$), the convective heat transfer
 294 coefficient of the internal hot wall side ($W/m^2.K$) and the convective heat transfer
 295 coefficient of the external cold wall side ($W/m^2.K$) respectively.

296 Considering that $T_i = 20$ °C and $T_e = 0$ °C and solving the above equations by an
 297 iterative calculation procedure as described by Laaroussi and coll. (2017), a total heat flux
 298 ΦT is obtained equal to 0.176 W through the total brick surface equal to 0.0122 m^2 .

299

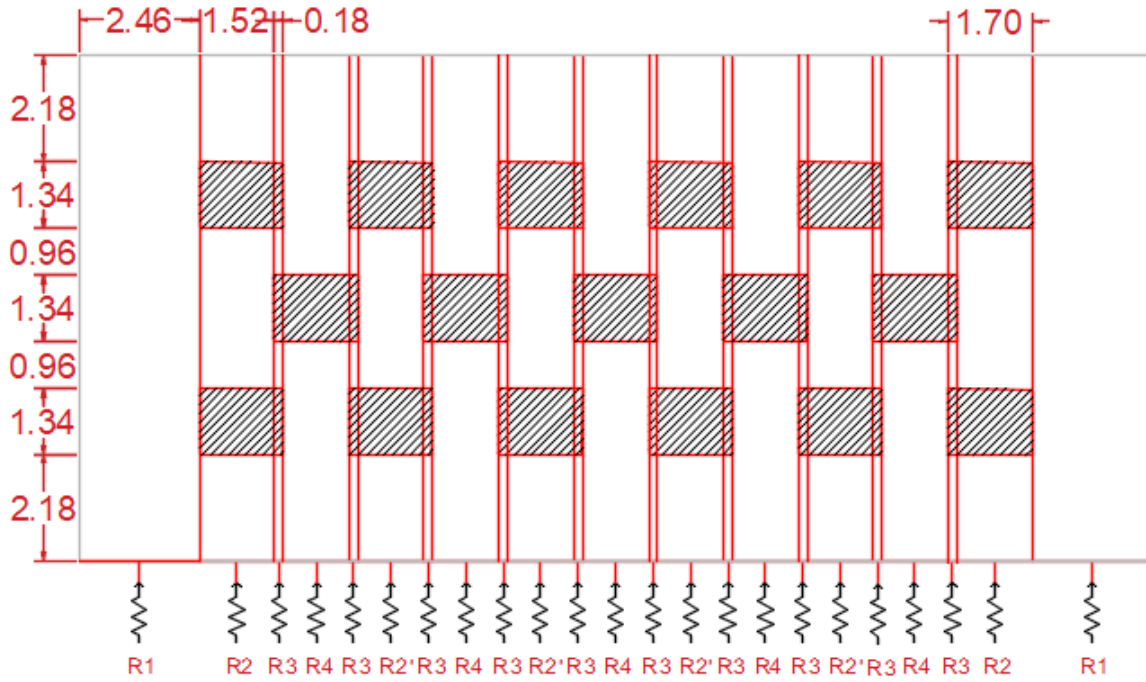


Figure. 9. Equivalent simplified scheme of S/BP brick

300 II.2.4 Equivalent thermal resistance of S/BP brick

301 The equivalent thermal resistance of S/BP can be concluded as follows, by using Eq.
 302 (25) and Eq. (26):

$$R_{brick} = \frac{1}{U} - R_{s,i} - R_{s,e} \quad (25)$$

$$U = \frac{\Phi T}{ST(T_i - T_e)} \quad (26)$$

303 Where U is the thermal transmittance $W/(m^2 \cdot K)$ and ST is the total surface of the S/BP brick
 304 (m^2) crossed by the heat flux ΦT . Therefore, the calculation described above leads to $U =$
 305 $0.721 W/m^2 \cdot K$ and $R_{brick} = 1.218 m^2 \cdot K/W$.

306 III. Experimental set up

307 III.1 Bricks manufacturing

308 In this work, bricks were constructed in a similar matter as described by Costantine
 309 et al. (Costantine et al.2020) and an optimal S/BP 40% mass ratio of was adopted as shown
 310 by Karaky et al. (2018, 2019). A water/beet pulp mass ratio was chosen equal to 2.5 and dry
 311 beet pulps were soaked in water for 2 hours until saturation. In a next step, potato starch
 312 granules were mixed manually for 10 min with the saturated wet pulps until complete

313 homogenization. Afterwards, the obtained mixture was placed in an autoclave and heated
314 for 30 min at 120° C and then poured into wooden molds. All bricks were produced and
315 compacted under a pressure of 0.044 MPa, then frozen at -80° C and dried using a freeze-
316 dryer which provided a more effective drying with a minimal shrinkage percentage of 2.5 %
317 while preserving a higher sample surface quality as compared with pulsed hot air drying.

318 III.2 Wall construction

319 In order to study the thermal performance at the wall scale, a 100 cm x 100 cm wall
320 having a surface area equal to 1 m² and a thickness equal to 10.3 cm was constructed using
321 S/BP hollowed bricks. All bricks used to construct the wall are considered uniform having
322 the same dimensions (L = 21.85 cm, w = 10.3 cm and h = 5.6 cm with internal holes
323 diameters D = 1.7 cm. The bricks were cemented together by a 1cm layer of S/BP identical
324 mix for the sake of material homogeneity. The binder used had similar material composition
325 to the S/BP bricks with the same mass ratio equal to 0.4. The resulting wall was dried at
326 ambient temperature for several months in a ventilated room with regular fan ventilation
327 prior to study. The wall was perfectly fitted and sealed into a wooden frame as shown in Fig.
328 10 and Fig. 11, whereas only an opening of 70 cm x 70 cm was maintained in the wooden
329 enclosure on the center of both sides of the wall, which represents the area in contact with
330 the hot and cold sides of the bi-climatic chamber. Therefore, the heat exchanged between
331 the two hot and cold chambers through the wall was limited to this area only since all lateral
332 surfaces of the wall are well insulated in order to prevent any lateral heat exchange with the
333 environment.

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Figure. 10. side enclosure with wooden frame

Figure. 11. S/BP wall enclosure

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III.3 Thermal performance

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III.3.1 Equivalent thermal resistance of a S/BP brick

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After production, the S/BP wall was inserted and tightened between the two enclosures of a bi-climatic chamber THERMO³ as shown in Fig. 12. This device allowed to measure the heat passing through the wall under different thermal conditions as shown in Fig. 13. Each chamber was insulated with a 10 cm thickness of polyurethane, and was equipped with 8 digital temperature sensors distributed throughout the volume and on the surface of the wall to be tested. Temperature uniformity was ensured by mechanical ventilation without disturbing the natural convection which was maintained between the surface wall and surrounding zones.

346

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The density of the heat flux through the wall inserted inside the bi-climatic chamber can be obtained by using the following Eq. (27):

$$\Phi_p = \frac{Pe}{Sm} \quad (27)$$

348

349

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Where φ_p , Pe and Sm are the density of the heat flux (W/m^2), the electrical power developed by the heating chamber of the device (W) and the surface of the S/BP wall in contact with the heating chamber (m^2) respectively.

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Finally, the thermal resistance of the S/BP wall was calculated using Eq. (28) while the equivalent thermal resistance of this wall was calculated using Eq. (29) as follows:

$$R = \frac{Sm \cdot (T_c - T_f)}{Pe} \quad (28)$$

$$Req = R + \frac{1}{hc} + \frac{1}{hf} \quad (29)$$

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Where R , T_c , T_f are the thermal resistance of the S/BP wall ($m^2 \cdot K/W$), the temperature of the wall surface in contact with the hot zone, the temperature of wall surface in contact with the cold zone respectively and Req , hc , hf are the equivalent thermal resistance of the S/BP wall ($m^2 \cdot K/W$), the convective heat transfer coefficient on the hot wall side ($W/m^2 \cdot K$) and the convective heat transfer coefficient on the cold wall side ($W/m^2 \cdot K$) respectively.

358 Table 5 shows the thermal conditions imposed in the bi-climatic chamber at steady state
 359 while the experimental results for the thermal properties of the S/BP wall and the
 360 equivalent thermal properties of the same wall are shown in tables 6 and 7 respectively.

361 **Table 5**

362 Thermal conditions imposed in the bi-climatic chamber at steady state

363

Sm (m ²)	Hot air average temperature (°C)	Tc (°C)	Cold air average temperature (°C)	Tf (°C)	Heat flux (W)
0.64	27.96	26.15	-0.01	1.84	14.19

364 **Table 6**

365 Conditions imposed in the bi-climatic chamber at steady state regime

366

R (m ² .K/W)	Wall thermal transmittance (W/m ² .K)	Equivalent wall thermal conductivity (W/m.K)	Heat flux density (W/m ²)
1.10	0.91	0.094	22.18

367

368 **Table 7**

369 Equivalent S/BP wall thermal properties

370

Req (m ² .K/W)	Equivalent wall Thermal transmittance (W/m ² .K)	hc (W/m ² .K)	Hf (W/m ² .K)
1.26	0.79	12.2	12.0

371



Figure. 12. S/BP wall insertion in the Thermo³ device

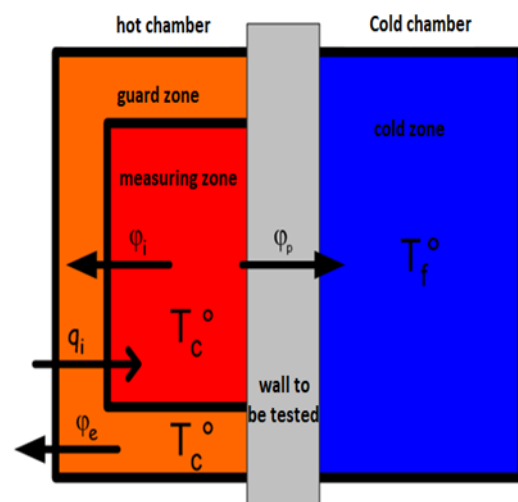


Figure. 13. heat transfer inside a bi-climatic chamber

372 Experimental results show a thermal resistance of the S/BP composite equal to 1.10 m².K/W
373 which is slightly lower compared to the results obtained by the analytical calculations (1.218
374 m².K/W) and numerical study (1.180 m².K/W), which can be probably attributed to minor
375 measurements inaccuracies. The equivalent thermal resistance comparison between
376 numerical and experimental of S/BP composite is shown in Fig. 14.

377

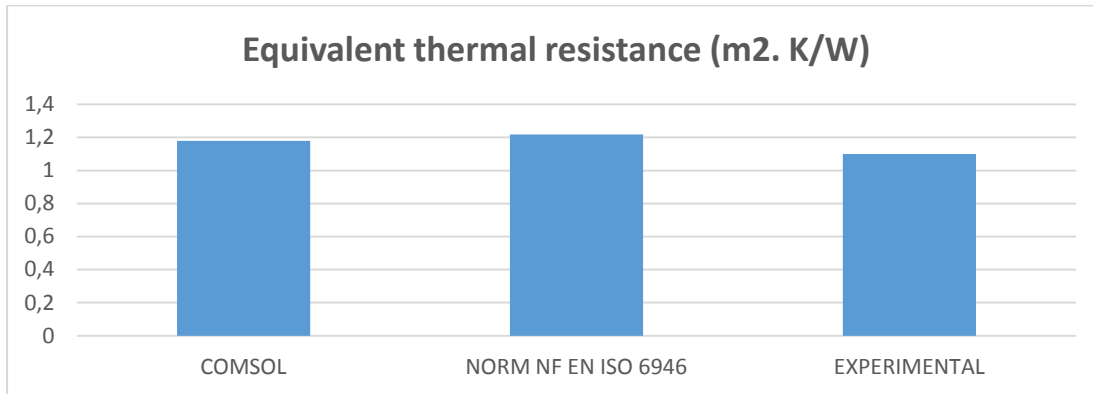


Figure. 14. Equivalent thermal resistance comparison between numerical and experimental of S/BP composite

378

III.3.2 Thermal imaging

379 The S/BP wall originally stored at 17°C and RH 50% for more than a month, was fixed
380 to the hot climatic chamber of the Thermo³ device on one side and kept exposed to a
381 constant ambient temperature equal to 17°C on the other side. A constant temperature of
382 40°C and RH 50% inside the hot chamber was imposed to the air in contact with the surface
383 of the wall and additionally, all lateral surfaces of the wall were well insulated in order to
384 prevent any lateral heat exchange with the environment as shown in Fig. 15.



Figure. 15. S/BP wall fixed from one side to the hot climatic chamber and exposed to ambient temperature from the other side

385 In order to analyze the heat transfer and temperature variation and distribution over the
386 entire exposed wall surface, highly precise thermal images were recorded using the
387 varioCAM HD thermography camera, which combines high-resolution image sensors
388 equipped with optomechanical resolution enhancement technology. This type of equipment
389 is widely used in building thermography for tracing heat and energy losses in the thermal
390 insulation of buildings with a non-contact process. The thermography camera has a
391 maximum image resolution of 2048x1536 IR pixels (RE mode), a spectral range between 7.5
392 μm and 14 μm , a temperature measuring range between -40°C and $+1200^{\circ}\text{C}$, a thermal
393 resolution $< 50\text{ mK}$ and an accuracy of 1.5 K or 1.5% (JENOPTIK, n.d.). It was placed in front
394 of the surface of the S/BP wall exposed to the ambience and hourly thermal images were
395 taken as shown in Fig. 16



Figure. 16. Thermal imaging recording of S/BP wall surface exposed to ambient temperature

396 While table 8 shows the recorded values of the minimum, maximum and average wall
 397 surface temperature of the side exposed to ambient temperature. Fig. 17 shows an increase
 398 of only 3.21°C of the average surface wall temperature after 450 minutes for a 23°C air
 399 temperature difference between both wall sides, which reflects the remarkable thermal
 400 performance of the studied wall.

401 **Table 8**

402 Maximum, minimum and average wall surface temperature of the side exposed to the
 403 ambient temperature obtained by thermal imaging with respect to time in minutes

404

	0	90	120	180	240	300	360	450
Tavg (°C)	17.68	18.45	18.79	19.50	19.74	20.21	20.58	20.89
Tmin (°C)	17.07	16.97	17.64	18.57	18.74	19.06	19.28	19.59
Tmax(°C)	18.07	19.41	19.91	21.29	22.04	22.78	23.36	23.50

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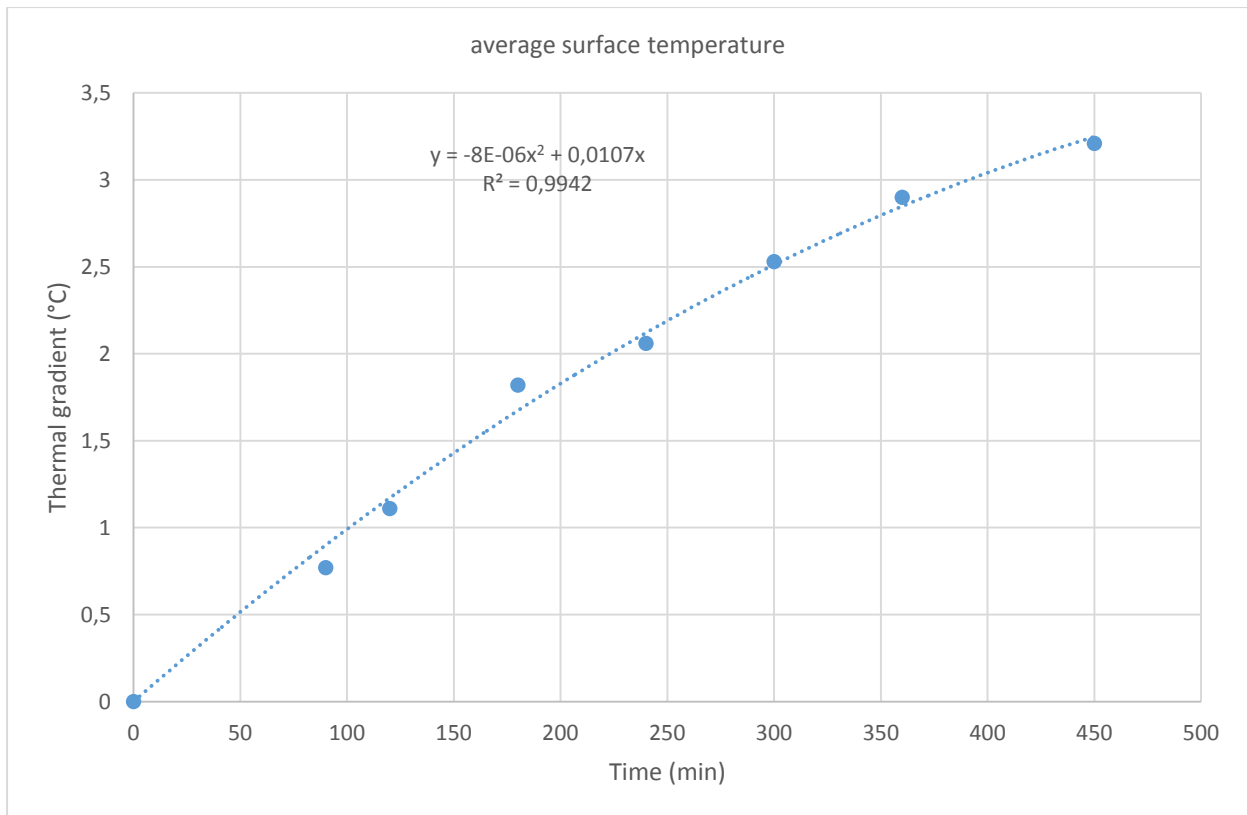


Figure. 17. Average surface temperature variation of side wall exposed to ambient temperature

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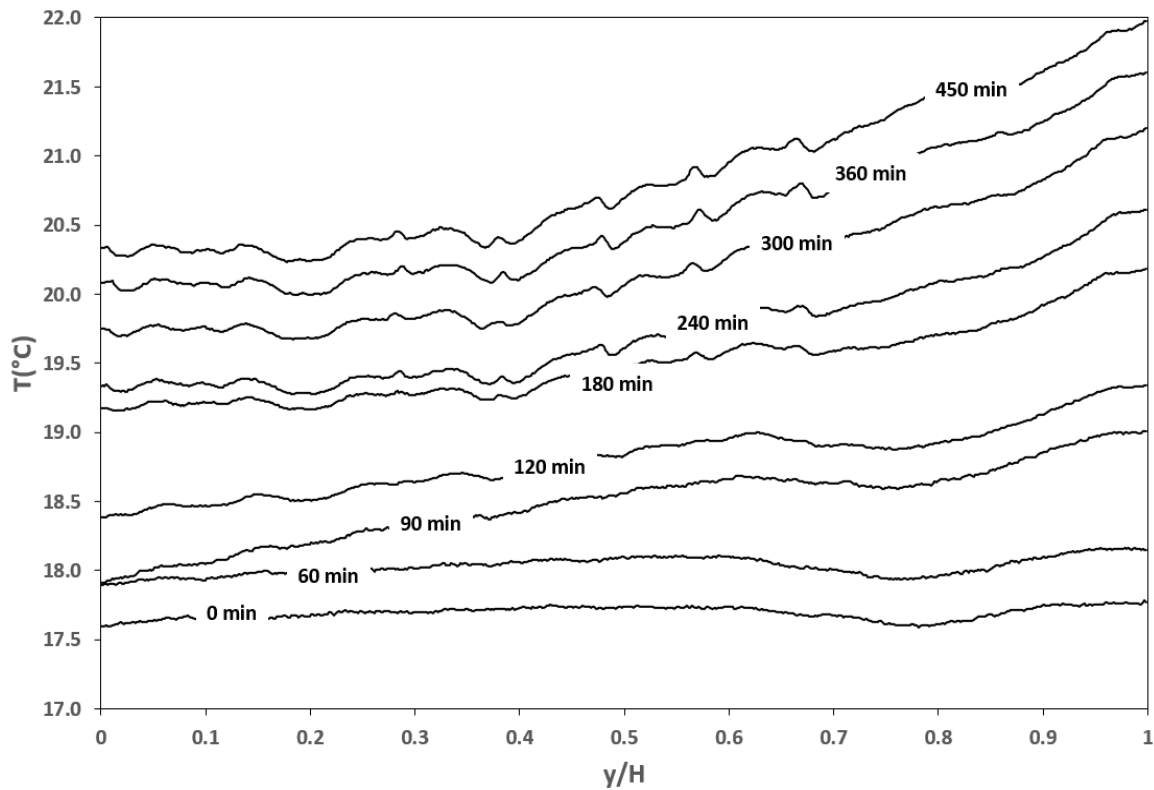


Figure. 18. Wall surface temperature gradients with respect to height and time

408 Moreover, with H symbolizing total height of the surface wall exposed to ambient
 409 temperature and y/H symbolizing partial wall heights varying from 0 to 1 (bottom and top of
 410 the wall respectively), Fig. 18 reveals various surface temperature gradients in terms of wall
 411 elevation with respect to time. The results show an increase of surface temperature with
 412 height which can be explained by the natural convection phenomenon and whereas a higher
 413 temperature difference between the bottom and top of the wall was recorded with time
 414 due to average wall temperature increase. Finally, Fig. 19 shows the recorded images by
 415 thermography reflecting the temperature variation all over the wall surface exposed to the
 416 ambient temperature with time.

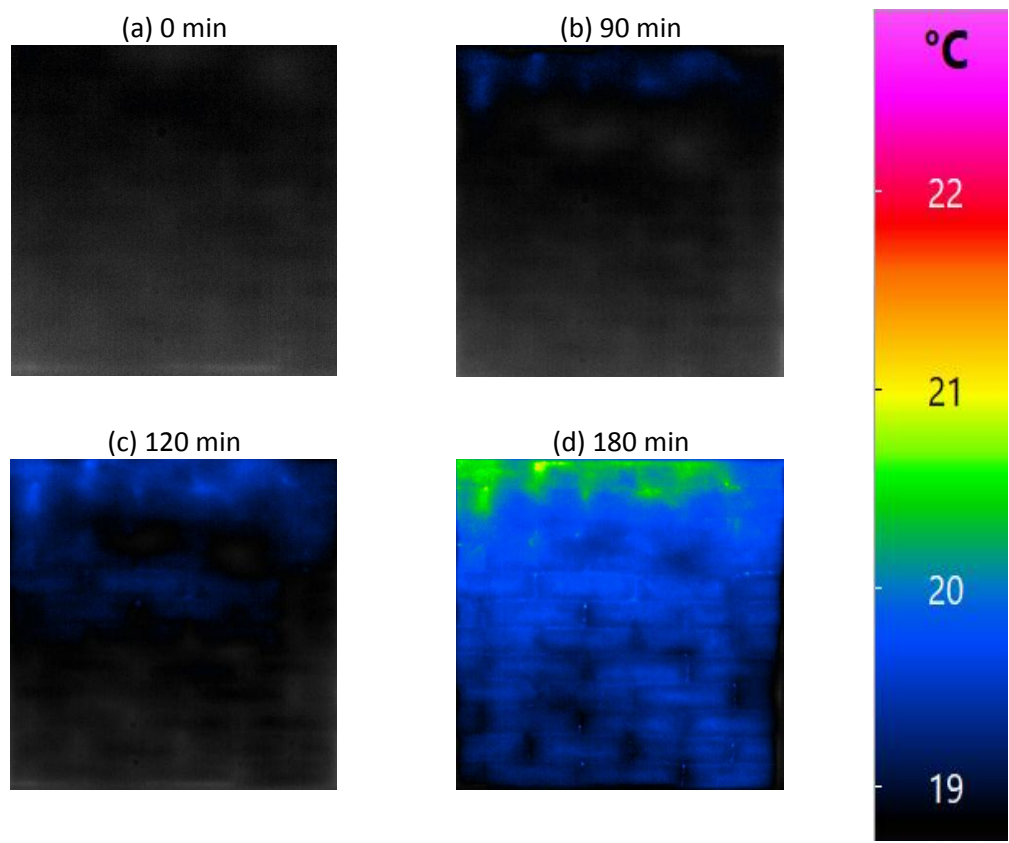
417 The results show a nearly uniform temperature distribution horizontally with a slight
 418 variation at the center of the perforated S/BP brick mainly due to the presence of air inside
 419 and another slight variation at the joints of the brick probably due to small difference in
 420 material amounts.

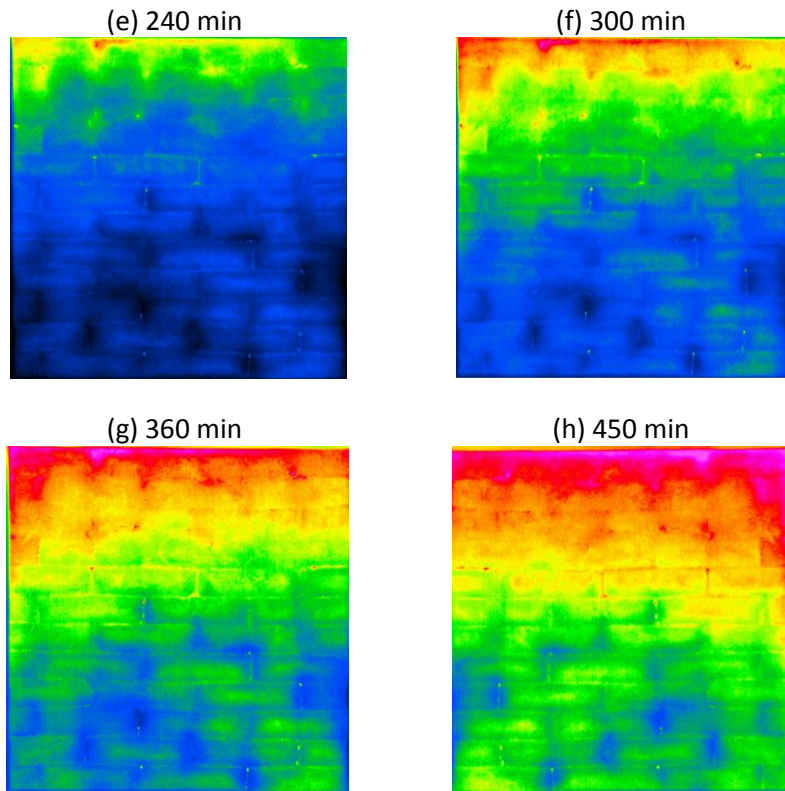
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441 Figure. 19. Visible images by thermography that depict the distribution of temperature differences on the S/BP
 442 wall surface exposed to ambient temperature and recorded at: (a) 0 min, (b) 90 min, (c) 120 min, (d) 180 min,
 443 (e) 240 min, (f) 300 min, (g) 360 min, (h) 450 min.

444

445 **IV. Results and discussions**

446 In this study, the thermal conductivity of the S/BP bio-composite was numerically,
 447 analytically and experimentally investigated. An equivalent thermal conductivity is obtained
 448 almost identical for all results around (ca 0.09 W/(m.K)).

449 Beet-pulp/starch composite presented a thermal conductivity slightly lower than other bio-
 450 based composites thermal conductivities ranging from 0.0693 to 0,0793 W/ (m.K) for grape
 451 by-products/starch (Badouard et al. 2021), 0.06 to 0.07 W/ (m.K) for hemp/Wheat starch (
 452 Bourdot et al. 2017), 0.055 to 0.088 W/ (m.K) for bamboo fiberboards/Bone glue mixed with
 453 sodium lignosulfonate (Mao et al. 2017), 0.047 to 0.055 W/ (m.K) for mixture of reed and
 454 straw/Rosin obtained from pine resin (Bakatovich et al. 2022). All these studies revealed
 455 that the thermal conductivities of bio-based composites highly depend on their type,
 456 formulations and densities along with binder type and bio-composites to binder mass ratio.

457 Table 9 shows density and thermal conductivity comparison between the S/BP bio-
 458 composite, other natural bio-composites investigated for building insulation use and other
 459 conventional building insulation materials currently used in construction found in the
 460 literature.

461 Overall, it can be concluded that the S/BP bio-composite can be considered as an effective
 462 material for building insulation use.

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476 **Table 9**
 477 Density and thermal conductivity comparison of S/BP with other natural and conventional
 478 insulation materials used in construction.

Material	Density (kg/m ³)	Thermal conductivity (W/m.K)	References
Glass wool	10–100	0.03–0.05	Kumar & coll. (2020)
Rock wool	40–200	0.033–0.04	
Expanded Polystyrene	18–50	0.029–0.041	
Extruded Polystyrene	32–40	0.032–0.037	
Foamed Glass	100–200	0.038–0.055	
Cellulose	30–80	0.037–0.042	Collet & coll. (2014)
Hemp concrete	300-500	0.0971-0.1659	
Cellular concrete	600	0.14	Maalouf & coll. (2014)

Earth block	1850	1	
Solid brick	1950	0.87	
Concrete	2300	1.75	
Grape by-products/Starch	227-433	0.0693-0,0793	Badouard & coll. (2021)
Hemp/Wheat starch	182-187.9	0.06–0.07	Bourdot & coll. (2017)
Bamboo fiberboards/Bone glue mixed with sodium lignosulfonate	311-538	0.055-0.088	Mao & coll. (2017)
Mixture of reed and straw/Rosin obtained from pine resin	160-224	0.047-0.055	Bakatovich & coll. (2022)
Beet pulps/ Potato starch	360	0.094	This Study

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V. Conclusions

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This work focuses on the study of the thermal performance of a low cost and bio-sourced material based on starch and beet-pulp (S/BP) as building insulation material on a wall scale level. For this purpose, a numerical study was elaborated using the commercial software COMSOL in order to determine the best holes distribution profile for a high thermal resistance of a brick while at the same time satisfying a good mechanical behaviour. An equivalent thermal resistance equal to $1.180 \text{ m}^2 \cdot \text{K/W}$ was obtained for a brick (21.85 cm x 10.3 cm x 5.6 cm) having a total number of 17 holes distributed in 3 rows. Afterwards, the obtained result was compared to an analytical calculation based on the norm NF EN ISO 6946 (2017) for the same brick configuration resulting in an equivalent thermal resistance equal to $1.218 \text{ m}^2 \cdot \text{K/W}$

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In a later stage, an experimental thermal study was made on a S/BP brick wall with the same configuration elaborated above by inserting this wall in a bi-climatic chamber. A slightly lower equivalent thermal resistance of the wall equal to $1.10 \text{ m}^2 \cdot \text{K/W}$ was obtained, which could be due to small measurements inaccuracies.

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Therefore, the obtained results reflected a good agreement between the numerical and experimental results. Moreover, the results revealed that the studied S/BP composite had a high thermal performance compared to other insulation materials used in building construction.

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Finally, highly accurate thermal imaging was performed on the S/BP brick wall exposed to a constant temperature of 40°C on one side and to ambient temperature of 17°C

502 on the other side in order to analyze the heat transfer by studying the distribution of the
503 temperature differences on the S/BP wall surface. Promising results were obtained where a
504 nearly uniform temperature distribution was found horizontally and an increase in
505 temperature from the bottom of the wall to the top was shown due to natural convection.
506 Moreover, the thermal images reflected the good thermal inertia of the wall since an
507 increase of only 3.21°C of the average surface wall temperature was shown after 450
508 minutes of exposure to a constant temperature of 40°C while maintaining a steady room
509 temperature of 17°C at constant relative humidity equal to 50%.

510 Further investigations are also ongoing using S/BP hollowed bricks at wall scale to study the
511 hygric behaviour of this material.

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514 pellets necessary for the specimens manufacturing.

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616 **VIII. List of symbols**

Symbol	Definition
$R_{a,x,y}$	Thermal resistance of an air space limited by points x and y ($m^2.K/W$)
$h_{a,x,y}$	Heat transfer coefficient by natural convection/conduction between the cold and hot surfaces of an air space limited between points x and y ($W/m^2.K$)
$h_{r,x,y}$	Heat transfer coefficient by radiation between two isothermal parallel surfaces of an air space limited between points x and y ($W/m^2.K$)
$T_{h\ hole_x}$	Average isothermal hot temperature of vertical surface limiting air space at point x (K)
$T_{c\ hole_y}$	Average isothermal cold temperature of vertical surface limiting air space at point y (K)
$d_{x,y}$	Air space thickness between points x and y (m)
$b_{x,y}$	Air space width between points x and y (m)
ϵ_x	Total hemispherical emissivity of the hot surface at point x limiting air cavity
ϵ_y	Total hemispherical emissivity of the cold surface at point y limiting air cavity
ρ	Density (kg/m)
C_p	Specific heat capacity (J/kg.K)
λ	Thermal conductivity (W/m.K)
μ	Dynamic viscosity (kg/m.s)
ν	Kinematic viscosity (m^2/s)
β	Thermal expansion coefficient (K^{-1})
Pr	Prandtl number
α	Thermal diffusivity (m^2/s)
T_1, T_2	Average hole surface temperatures (k)
D	Hole diameter (m)
L	Hole equivalent length (m)
$R_{x,y}$	Thermal resistance of S/BP brick between points x and y ($m^2.K/W$)
$e_{x,y}$	Thickness of S/BP brick limited by points x and y (m)
λ_m	Thermal conductivity of S/BP bio-composite (W/m.K)
Φ	Heat flux (W)
S	Surface Area (m^2)

T _i	Room Internal temperature (K)
T _e	Room external temperature (K)
R _{s,i}	Inner surface thermal resistance due to convection (m ² .K/W)
R _{s,e}	External surface thermal resistance due to convection (m ² .K/W)
h _i	Convective heat transfer coefficient of the internal hot wall side (W/m ² .K)
h _e	Convective heat transfer coefficient of the external hot wall side (W/m ² .K)
U	Thermal transmittance (W/m ² .K)
P _e	Electrical power developed by the heating chamber (W)
J	Surface radiosity (W/m ²)
e _b	Blackbody total emissive power (W/m ²)
ρ _d	Surface reflectivity
G	Surface irradiation (W/m ²)
G _{m(J)}	Mutual surface irradiation (W/m ²)
G _{amb}	Ambient irradiation (W/m ²)
F _{amb}	Ambient view factor
ε _{amb}	Ambient surface emissivity
n	Transparent media refractive index
σ	Stefan-Boltzmann constant (W/(m ² .K ⁴))
q _{r,net}	Net radiative heat flux density (W/m ²)

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