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1 **Investigation into the use of thermoelectric modules as an alternative to**
2 **conventional fluxmeters: application to convective and radiative heat flux**
3 **in buildings**

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19
20
21 **Abstract**

22
23 The present work aims to propose the use of Peltier modules for the superficial heat flux measurement, as an
24 alternative to conventional heat flux sensors. In this study, the function of Peltier modules (TEM) as heat flux
25 sensors is compared to the Captec® heat flux sensors (FGT), based on the premise that conventional heat flux
26 sensors such as Captec® have been proven to have acceptable performance for the heat flux measurement, i.e.,
27 conduction, convection and radiation. A simple measurement device and a simple general formulation for
28 decoupling the convective and radiative parts from the heat flux measurement are proposed. The latter are
29 implemented in an experimental case presenting weak convective and radiative heat fluxes, using a black-shiny
30 couple of Peltier modules and a black-shiny couple of Captec. The radiative part was found to be the same when
31 comparing FGT and TEM measurements. However, the convective part when using TEM measurements was
32 found to be around two times larger than when using FGT measurement. It has been encountered that this
33 difference is better explained by the geometrical and thermal properties of both sensors.

34
35 Keywords: Heat flux measurement, thermoelectric modules, Peltier modules, heat flux sensor, convective heat
36 flux, radiative heat flux.

37
38
39 **1. Introduction**

40 In various thermal engineering fields, the needs of predicting models gradually require a more precise
41 estimation of the real value of the thermal stresses, e.g., superficial heat transfer, absorbed heat flux, to verify the
42 reliability model-measurement when accounting for such thermal stresses. For instance, in the calculations of
43 cooling or heating needs in order to maintain the internal thermal comfort in buildings; in the characterization of
44 walls to determine the incoming and outgoing heat flux through the walls [1,2]; in the estimation of convective
45 and radiative heat transfer in heat exchangers [3]; in the estimation of the convective heat transfer in ovens for
46 drying [4]. In this context, thermal engineers had proposed more than 30 years ago a widely used technique for
47 heat flux measurement able to estimate the heat flux through the surface (conduction), and at the surface
48 (convection and radiation). This technique is based on the use of flat-plate heat flux sensors (also known as
49 conventional or classical heat flux meters); sensors that are about ten times more expensive than a Peltier module
50 of the same size. For example a conventional heat flux sensor of 4 x 4 cm² of type Captec® costs around 600 €,
51 whereas a Peltier module of this size costs around 20 €. Thus, this has led researchers to think of an alternative
52 way, proposing a technique based on the use of single-stage Peltier modules for the heat flux measurement.
53 Another leading cause lays in that, although Peltier modules are not designed to measure heat flux, their use is
54 very attractive because, when used for this purpose, they present stronger thermoelectric power compared to a
55 Captec® of the same size and even one of a bigger size, which allows in principle to measure weak thermal loads
56 more precisely.

57 However, Peltier modules response time (about one minute) limits their implementation to somewhat slow
58 processes, due to the materials used for its fabrication. For example, in buildings, a significant change in the
59 evolution of the envelope temperature can be detected in a couple of hours, which indicates that the thermal stresses
60 also present significant variation on similar duration. In such a case, a heat flux sensor with a quick response time
61 is not absolutely needed.

62 Moreover, although Peltier modules has not been employed as large as conventional heat flux sensors for the
63 heat flux measurement, according to the reported literature, it has been found that the former works satisfactory
64 well enough in the estimation of the Solar radiation heat flux [5]. Conversely, in the estimation of the convective
65 heat flux, it has been found that Peltier modules overestimate its magnitude by about a factor of two [6,7].
66 Therefore, for all these reasons and based on the premise that conventional heat flux sensors such as Captec® has
67 been proven to perform well enough [3], it was found quite interesting to study and compared the use of Peltier
68 modules with Captec, to conclusively propose a thorough methodology for implementing the former as an
69 alternative to the latter, in the estimation of the superficial heat transfer (convection and radiation).

70

71 1.1. Background on the heat flux measurement with flat-plate sensors

72

73 In this type of heat flux meters, the measurement is based on the Seebeck effect. The voltage difference U at
74 the sensor electrical terminals is proportional to the heat flux traversing the sensor q , both related by a
75 thermoelectric coefficient [1,3,8]. This before can be represented by a simple equation, as follows:

76

$$77 \quad q = \frac{U}{K} \quad [\text{W}\cdot\text{m}^{-2}] \quad (1)$$

78

79 where U is normally expressed in μV and q is the measured heat flux or traversing the sensor. U can take positive
80 and negative values, depending on the heat flux direction and on the polarity connection of the sensor electrical
81 terminals. The coefficient K is the sensitivity value of the sensor, which groups its thermoelectric properties, e.g.,
82 the Seebeck coefficient a_{eq} , the total number of thermocouple junctions N , and the thermal conductivity λ_{eq} ;
83 normally expressed in $\mu\text{V}/\text{W}\cdot\text{m}^{-2}$ and it is usually determined by calibration techniques. The relation between these
84 magnitudes could be demonstrated to be equal to the following expression:

85

$$86 \quad K = \frac{Na_{eq}e}{\lambda_{eq}} \quad [\mu\text{V}/\text{W}\cdot\text{m}^{-2}] \quad (2)$$

87

88 where e corresponds to the thickness of the active section of the sensor. Expression 2 results from replacing
89 Fourier's conduction equation, and the thermoelectric relationship between voltage and temperature difference
90 ($U = a\Delta T$), into equation 1.

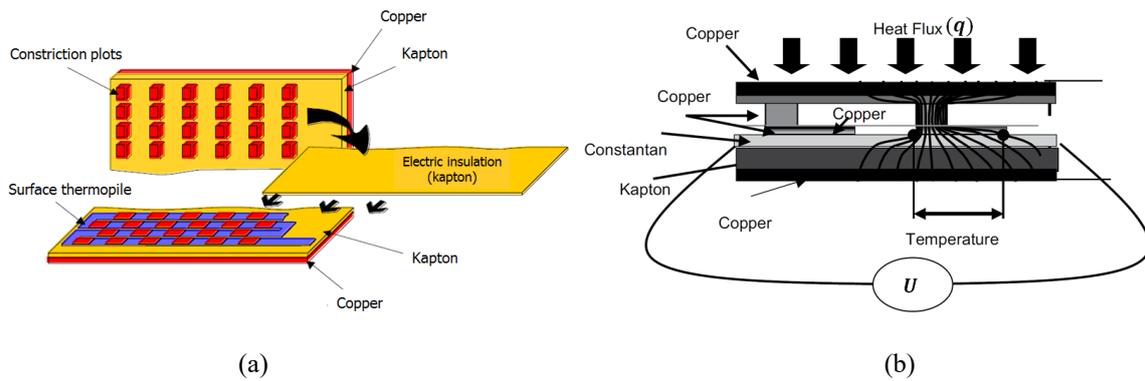
91 Moreover, the value of the sensitivity K might vary with the temperature of the thermoelectric junctions due
92 to the thermoelectric properties of the materials used for this kind of sensors. This might rarely happen when the
93 sensor is manufactured with metal alloys. However, when using semiconductors for the thermocouples junctions,
94 K may vary, since their Seebeck coefficient and thermal conductivity do vary with the average temperature of the
95 junctions; although a significant variation might only be encountered when the temperature rises above some
96 hundreds of degrees [9].

97

98 1.1.1. Conventional heat flux sensor: Tangential temperature gradient

99 In the conventional heat flux sensor known as the Théry-type (referred here as FGT, which stands for Fluxmètre
 100 à Gradient Tangential in French), several and very small thermocouple junctions are connected in series, i.e., as a
 101 thermopile, distributed all over the surface of an insulated support (based on the printed circuit board technique).
 102 This support is then covered by two plates of copper, on each side (see figure 1 (a)). When both plates of this
 103 embedded element are submitted to different temperatures, each of the thermocouple junctions generates a voltage
 104 difference due to the temperature gradient and the Seebeck effect principle (see figure 1 (b)). These sensors are
 105 also designed as to measure the temperature at a middle plane between both copper plates [3].

106



107

108

109 Figure 1. Structure of Captec® heat flux meter: (a) Composition, and (b) transversal side view with heat flux
 110 lines [3].

111

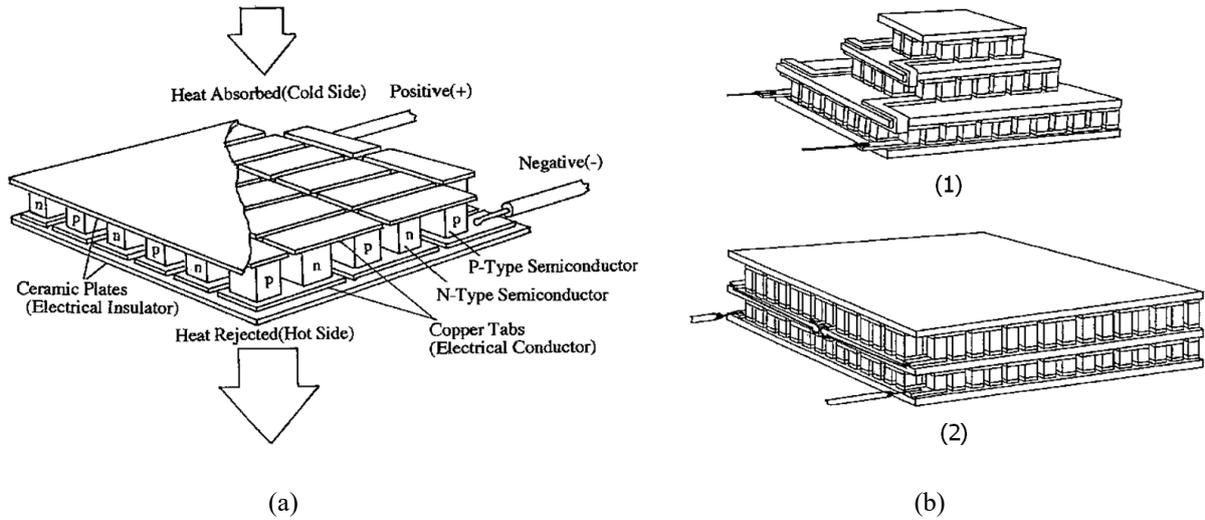
112 This type of conventional heat flux sensors are widely found in the market, for instance, Captec® enterprise, offers
 113 square heat flux meters with a dimension range between 5 x 5 mm² and 300 x 300 mm² with a thickness of about
 114 0,5 mm or thinner. Depending on these dimensions, their sensibility value can vary from some $\mu\text{V}/\text{W}\cdot\text{m}^{-2}$ to around
 115 a hundred of $\mu\text{V}/\text{W}\cdot\text{m}^{-2}$, for instance, a 50 x 50 mm² presents a sensibility of around 20 $\mu\text{V}/\text{W}\cdot\text{m}^{-2}$, and a 150 x
 116 150 mm² presents a sensibility of around 120 $\mu\text{V}/\text{W}\cdot\text{m}^{-2}$; where their cost may reach the 600 euros each.

117

118 **1.1.2. Thermoelectric modules or Peltier modules**

119 Thermoelectric modules, also known as Peltier modules (referred here as TEM), are composed of several
 120 thermocouple junctions connected electrically in series and thermally connected in parallel, integrated between
 121 two ceramic plates [9] (see figure 2 (a)). These thermocouple junctions consist of a n- and a p-type semiconductor
 122 materials connected by small and thin copper tabs; the most common semiconductor materials employed are
 123 quaternary alloys of bismuth, tellurium, selenium, and antimony, e.g., Bi₂Te₃. There are still modules without
 124 ceramic plates, which have the advantage of eliminating the thermal resistance of the ceramic plate. They also

125 have the disadvantage of mechanical fragility and require electrical insulation. The ceramic plates serve as a good
 126 electrical insulation and a high thermal conductance [9].



127
 128 (a) (b)
 129 Figure 2. General structure of a thermoelectric module: (a) A single-stage TEM, and (b) two different multistage
 130 TEM configurations [9].

131
 132 The thermoelectric properties of TEM vary with the average temperature of the thermoelectric n-p junctions
 133 (usually called: elements); generally, a polynomial correlation with second-order temperature terms is used. For a
 134 thermoelectric material of n- and p- type, the average value of the properties is used (value of n + value of p)/2
 135 [9]. In addition to the thermoelectric material properties, the module is characterized by two other parameters: GF,
 136 which represent the geometric factor of a single thermoelectric element and is given by $GF = S_{element}/e_{element}$,
 137 and N the number of n plus the number of p elements (sometimes the couple terminology is used: number of
 138 couples (N/2) [9]. Moreover, a thermoelectric module or a single thermoelectric element can be characterized by
 139 the total electric resistance (Re_{TEM}) in Ω , the total Seebeck coefficient (a_{TEM}) in $V \cdot K^{-1}$, and the total thermal
 140 conductivity (λ_{TEM}) in $W \cdot K^{-1}$, respectively: $Re_{TEM} = N \cdot \rho_{element}/GF$, $a_{TEM} = N \cdot a_{element}$, and $\lambda_{TEM} = N \cdot$
 141 $\lambda_{element} \cdot GF$; the subscript “element” refers to the average value of the np thermoelectric couple.

142 These modules have been designed for many applications, for instance, in cooling application and electrical
 143 generation purposes; they name may differ depending on the application: thermoelectric cooler (TEC) where the
 144 TEM is use in “Peltier mode” and thermoelectric generator (TEG) where the TEM is use in “Seebeck mode”,
 145 respectively. When used as thermoelectric cooler [8], their main function is to extract the heat from the surface
 146 they are placed on. To accomplish this main function, the TEM is normally connected to a DC power source,
 147 which, when turned on and depending on the connection polarity, i.e., positive with positive and negative with

148 negative, will induced the creation of a temperature difference between both sides of the TEM. Each of the TEM
149 sides are normally called cold (T_C) and hot (T_H) side. Then, the cold side is placed onto the surface wanted to be
150 cool down and the hot surface is normally attached to a heat sink which is exposed to surrounding air; this heat
151 sink is intended to enhance the heat transfer (as the function of an extended surface). When these modules are used
152 for power generation, the hot and cold sides are disposed inversely and the electric terminals are connected to a
153 load to power it.

154 For heat flux measurement or heat flux detection, they work in an open circuit configuration when connected
155 to a multimeter or an acquisition system for data collection [5]. In this case, they follow a similar relation between
156 the voltage generated when a heat flux is traversing the module (see eq. 1). Even though they may have the
157 particularity of a K coefficient dependent on temperature due to the semiconductor materials of the thermocouple
158 junctions, and the time response is about one minute. The dimensions availability for this type of module is limited
159 with respect to the availability of conventional heat flux meters.

160

161 **1.1.3. Experimental and analytical approaches for splitting the convective and radiative heat exchanges**

162 **Two heat flux sensors with contrasted emissivity**

163

164 **Experimental approaches**

165

166 The measurement of superficial heat exchanges, i.e., convection and radiation, using FGT sensors and TEM,
167 have been a topic of interest of various researchers [1,3,11-16]. The interest lays in the possibility of splitting the
168 convection and radiation parts from the heat flux measurement. Here we are focused on the implementation of
169 such sensors for the estimation of both superficial heat exchanges; any other case was excluded. However, other
170 research works have been found regarding the implementation of such sensors in thermal characterization of walls
171 [2,4,11].

172 A technique to estimate the convection and radiation heat exchanges on a surface was implemented, consisting
173 of using two FGT sensors, where one was to be coated with a black surface and the other with a shiny surface.
174 Then, under the premise that the black and shiny surfaces had emissivity values close to 1 and 0 respectively, the
175 former was said to estimate the total heat flux (convection + radiation) and the latter to estimate the convection
176 heat flux on the rigid surface where they installed the sensors, e.g., heavyweight [9,18,19] and lightweight walls,
177 and isolate-type wall [11].

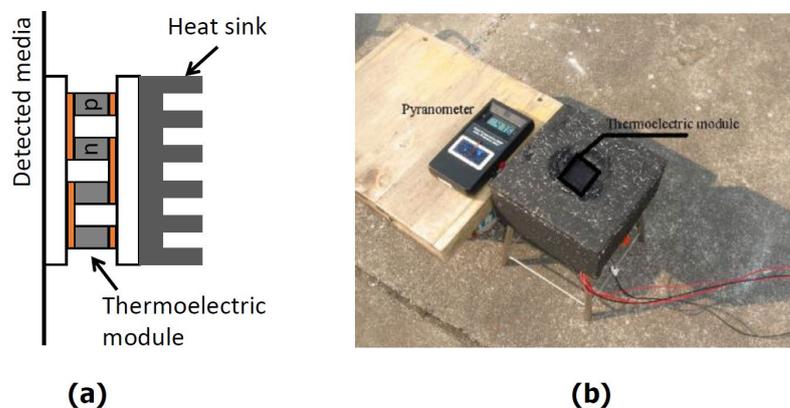
178 The disposition of the black and shiny heat flux sensors has differed from one study to the other, for instance,
179 they were placed next to each other by one side with a separation between them [18,20], and with no separation
180 between these two sensors [3,16]. A 10 cm separation between black and shiny was destined to the installation of
181 a thermocouple to measure the local air temperature [20].

182 The use of conventional heat flux sensors coated with a thin polished aluminum foil was proposed for
183 developing an experimental approach for measuring the convective heat transfer coefficient on heavyweight walls
184 [19]. Results were found to agree with values reported in the literature for the case of laminar free convection
185 along a vertical and isotherm heated plate.

186 More effort has been put into the estimation of the radiative heat flux. For instance, the development of a
187 radiative heat flux sensor, based on the same reasoning mentioned earlier [12,14]. In this case, several black and
188 shiny strips are placed next to each other intercalated and carefully wired as to superpose the electric potential
189 given by each strip. This type of sensor only estimates the radiative heat flux directly from the sensor electrical
190 response.

191 On the other hand, the implementation of Peltier modules is not as vast as for conventional heat flux sensors.
192 Peltier modules were used for heat flux detection ($4 \times 4 \times 0,09$ cm and $\sim 94 \mu\text{V}/\text{W}\cdot\text{m}^2$), at the rear face, through
193 an external wall of a building (see figure 3 (a)), where the front face of the wall was submitted to solar radiation
194 heat flux and the rear face, to indoor air conditions. A heat dissipater (or heat sink) was installed on the sensor
195 surface in contact with the indoor air, to increase the heat flow rate through the sensor. Experimental results were
196 compared with simulation, finding an average absolute difference of $6,7 \pm 2,7\%$ with maximum and minimum
197 values of 10,5% and 0,1%, respectively [5].

198



199

200 Figure 3. Experimental setup in Leephakpreeda 2012: (a) Installation on the rear face of a wall, and (b) for

201

measuring solar radiation heat flux.

202 These modules were also employed in the measurement of the solar radiation heat flux [5]. Here, the measurement
203 of one module coated with black surface (see figure 10 (b)) was compared with a pyrometer. It was pointed out
204 that satisfactory results were encountered as the average of the absolute differences was $4,8 \pm 3,9\%$, which lead to
205 conclude that the sensor measurement can be used for radiation heat flux without knowing the exact emissivity
206 value of a black coating.

207

208 **Analytical approaches**

209

210 A way to separate more accurately convective and radiative parts from the heat flux measurement was proposed
211 by [3]. The principle is based on a heat energy balance on the surface of the heat flux sensor, which is submitted
212 to convection (q_C) and radiation (q_R) heat exchanges. The total heat flux (q_T) on the sensor surface is equal to the
213 sum of q_C and q_R , and also, equal to the heat flux traversing the sensor (q):

214

$$215 \quad q_b = q_{C_b} + q_{R_b} \quad [\text{W}\cdot\text{m}^{-2}] \quad (3)$$

$$216 \quad q_s = q_{C_s} + q_{R_s} \quad [\text{W}\cdot\text{m}^{-2}] \quad (4)$$

217

218 It was stated that the heat flux measurement of each sensor (black and shiny), would have a convective and
219 radiative part, owing to the emissivity value of the black and shiny coating employed: a black paint (0,98) and a
220 thin aluminum foil (0,1), respectively, which are neither perfect emisors nor perfect reflectors. Thus, the convective
221 part was determined by subtracting the radiative part from the shiny sensor measurement. This radiative part was
222 estimated first, using the “classical radiosity method”, compared latter with numerical simulation on the Fluent
223 software. Results were also analyzed to study their dependence on the emissivity value of the black coating, by
224 changing the latter from 0,9 to 1 (a perfect black body). It was found that increasing the emissivity yield to an
225 increase in the total heat flux. Finally, it was concluded that the experimental procedure allows uncoupling the
226 convection and radiation parts from the measurement since the relative error obtained was 5% maximum between
227 the experimentation and numerical results. The heat flux levels in this experiment reached up to $350 \text{ W}\cdot\text{m}^{-2}$.

228 Douiri [16] based the analysis in equations 3 and 4, but wanted to estimate the convective heat transfer
229 coefficient (h_C) and the mean radiant temperature (here referred as T_{surr}), inside an oven. This consisted of
230 defining the convective part using Fourier's convection equation. For the radiative part, the Kirchhoff's hypothesis
231 for radiation heat transfer was employed. An expression for these two magnitudes h_C , T_{surr} depending on several

232 parameters, in which the temperatures (T_b , T_s) and emissivities (ε_b , ε_s : 0,93 and 0,1, respectively) of both sensors
233 played an important role, were drawn when solving the following, simultaneously:

234

$$235 \quad q_b = h_c(T_{air} - T_b) + \varepsilon_b \sigma (T_{surr}^4 - T_b^4) \quad [\text{W}\cdot\text{m}^{-2}] \quad (5)$$

236

$$237 \quad q_s = h_c(T_{air} - T_s) + \varepsilon_s \sigma (T_{surr}^4 - T_s^4) \quad [\text{W}\cdot\text{m}^{-2}]. \quad (6)$$

238

239 This approach is under two hypotheses: having only one convective coefficient for both sensors, and the
240 temperature measured by the sensor corresponds to that of its surface. The working heat flux ranges were of the
241 order of $1500 \text{ W}\cdot\text{m}^{-2}$ for convection, and $500 \text{ W}\cdot\text{m}^{-2}$ for radiation.

242

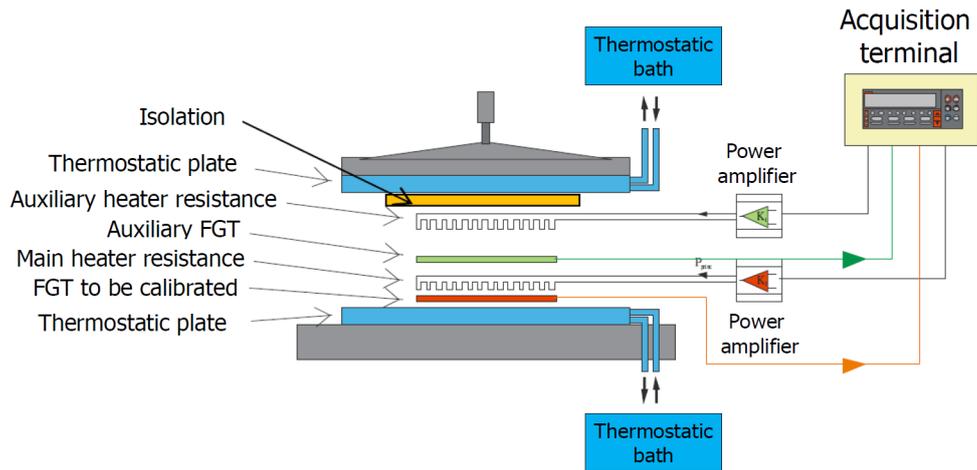
243 **1.2. Special concerns about the heat flux sensors and purpose of the research**

244

245 **1.2.1. Calibration methods for converting the electrical response into heat flux**

246 The calibration process for heat flux sensors is usually employed to determine the sensor sensibility value K
247 and the perturbations it introduces, regarding its equivalent specific thermal capacity C and its equivalent thermal
248 resistance Re [21]. The most common technique implemented for conventional heat flux sensors has been the
249 zero-flux method [3,11-13,16,20-22].

250 This technique consists, basically, in having the heat flux sensor inside a well-isolated-chamber device, which
251 contains (see figure 4): two flat heater resistors (having the same surface area as the sensor), an auxiliary heat flux
252 sensor, and two water-recirculation-plates connected to a thermostatically-controlled water bath (used as heat
253 sink). The sensor to be calibrated is placed over one of the water-recirculation-plates, and one of the heaters is
254 placed over the sensor. The auxiliary sensor is placed over the heater to detect heat dissipation in the opposite
255 desired direction. The auxiliary heater is placed over the auxiliary sensor, serving as heat flux compensation, which
256 power is regulated to maintain a null signal response from the second sensor, ergo, ensuring a zero-heat flux
257 through this sensor (wherefore the name zero-flux method).



258

259

Figure 4. Schematic of the calibration apparatus employed for the zero-flux technique [18].

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A profound study aimed to verify the sensibility value K , estimated by this calibration technique for the FGT, by implementing two numerical models of the multilayer system (see figure 4) using the governing equations of the physical phenomena that take place [22]. The simulation results showed the following: Only 39% of the sensibility value could be explained when using the perfect thermal-contact hypothesis between the copper and constantan layers inside the sensor, a value of the order of $1 \times 10^{-6} \text{ K} \cdot \text{m}^2 \cdot \text{W}^{-1}$ for the latter was enough to obtain a sensibility value identical to the one obtained by calibration, and the value of the contact resistance between the copper and constantan layers had a small influence on the sensor internal resistance R_e calculated, being consistent with the value obtained by calibration.

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On the other hand, [5] performed a different approach for the calibration of Peltier modules. The sensibility value was determined indirectly by estimating the total Seebeck coefficient and the equivalent thermal conductivity. For the total Seebeck coefficient, the module was energized with a DC power source, where the electrical response of the module and the temperature difference between its both sides were measured after turning off the DC power. The Seebeck coefficient results from the slope of a fitted linear regression model. The thermal conductivity was estimated by the classical conductive method.

276

1.2.2. Perturbations introduced by conventional heat flux meters: Captec® and TEM

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Various researchers have reported perturbations induced by both types of sensors when performing the heat flux measurement. For FGT, its measurements were compared with simulation results for two different cases, to estimate the errors in steady state [12] ($25 \times 25 \times 0,02 \text{ cm}$ and $35 \mu\text{V}/\text{W} \cdot \text{m}^{-2}$): (i) the sensors placed on a vertical

281 concrete wall (thermally heavyweight), (ii) the heat flux sensors placed on a polystyrene wall (thermal isolation).
282 For the first case, the convection heat flux was encountered to be overestimated by near 26% and the radiation
283 heat flux to be underestimated by practically 35%. For the second case, the error on the radiation heat flux was
284 around the -79% and on the convection heat flux was between 250 and 350%. For the case of isolate wall types, it
285 was concluded that the estimation of the convective and radiative components is complexed and a temperature
286 correction under the sensors is needed (in the sensor-wall interface, T_s'), where errors were said to be mainly
287 caused by the local temperature modifications on the wall surface, due to the presence of the sensors, which also
288 modifies the heat flow distribution through the wall thickness; this was also pointed out in [8,13,18].

289 In transient state, when a FGT sensor is placed onto a surface, it will absorb the heat flow at the same rate as
290 the wall if their thermal effusivity values are the same. The condition that the sensor heat storage capacity is
291 negligible concerning the heat flow traversing it, must be verified to perform measurements in a transient state
292 [12]. Finally, the measurement error is proportional to the mismatching between the sensor and the wall, i.e., the
293 difference between the effusivities $\sqrt{\lambda\rho c_p}$ and $\sqrt{C/R}$ of both, the sensor and the wall [12].

294 In the use of TEM as heat flux sensors, [5] compared experimental results, from the heat flow detection through
295 an external wall, with simulation, and pointed out that the amount of the detected heat flow through the wall was
296 not identical to the amount that would be detected without the use of a sensor. Two reasons were given to explain
297 this difference: The changes in the wall boundary conditions, and the effect of the thermal contact resistance
298 between the thermoelectric module and the wall.

299 Two types of heat flux sensors have been implemented in the present investigation: commercial TEM and FGT
300 of the type Captec®. As it has been encountered in the reported literature, FGT sensors are widely used having
301 been proven to perform satisfactory enough in the decoupling of the convective and radiative parts of the heat flux
302 measurements. Here, instead, we aim to propose a measurement device using TEM for the heat flux measurement
303 along with a rather simplify decoupling model. A comparison between TEM and FGT is made.

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305 2. Description and configuration of the setup for heat flux measurements

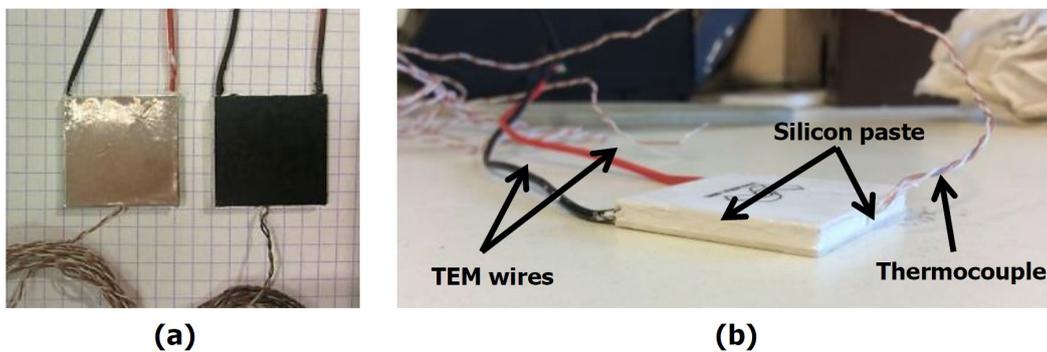
306

307 To perform the heat flux measurement, Peltier modules with dimensions of 3 x 3 x 0,48 cm and an average
308 sensitivity value of $239\pm 3 \mu\text{V}/\text{W}\cdot\text{m}^2$, and Captec heat flux sensors with dimensions of 15 x 15 x 0,05 cm with an
309 average K value of $125\pm 3\% \mu\text{V}/\text{W}\cdot\text{m}^2$ according to the manufacturer, are implemented here.

310 Since Peltier modules are not directly design for heat flux measurement as mentioned earlier, these modules
311 need to be calibrated in order to find the proportional constant coefficient that allow to convert their electrical
312 response into heat flux, as also mentioned earlier. Thus, the following section presents the calibration apparatus
313 and procedure followed to determine the sensitivity value K of our Peltier modules.

314 Before any implementation, the surface of the both the Peltier modules and Captec heat flux sensors were
315 covered with black and shiny coatings as to form couples of black-shiny heat flux sensors (one black and one shiny
316 sensor) (see figure 5 (a)). Also, the edges-sides of each Peltier module were covered with silicon paste with the
317 purpose of isolating the thermocouple inserted in the Peltier module from the surrounding air (see figure 5 (b)).

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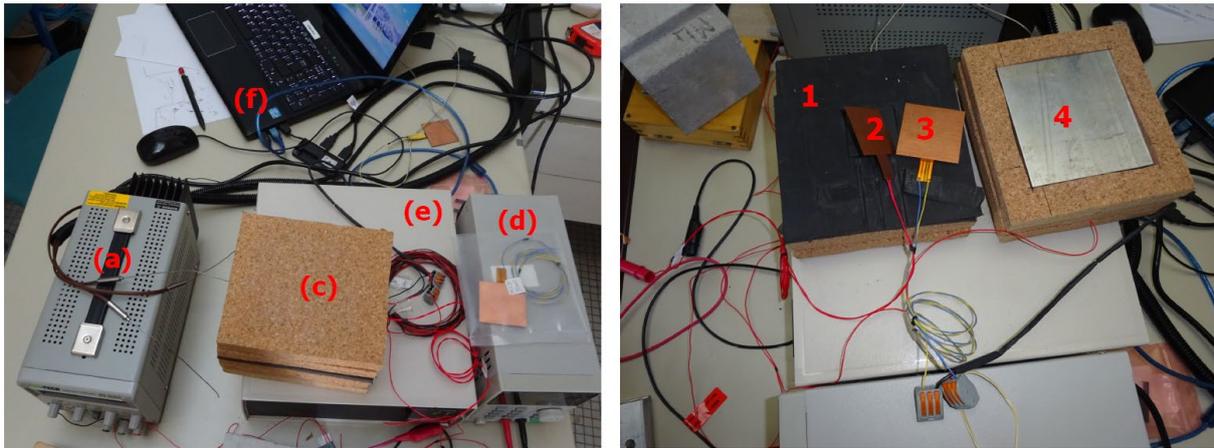
320 Figure 5. (a) Images of a shiny thermoelectric module, (b) black-shiny couple of TEM, and (c) Peltier module
321 with an inserted thermocouple wrapped with white silicon paste.

322

323 The calibration apparatus is shown in figure 6 and is based on the zero heat flux method consisting of: (a) a
324 power supplier ISO-TECH-IPS 303DD, (b) heavy blocks to assure contact, (c) a calorimeter with the heat and heat
325 flux meter inside, (d) a DC power supply VELLEMAN LABPS 3005D to power the heating resistance, and
326 together (e) and (f) group a PID controller RKC INSTRUMENT INC CB100/400/500/700/900 to regulate the
327 temperature of the calorimeter's chamber, and the measuring system with a LabView interface.

328 The calorimeter (see figure 6 left) is composed by four principal layers: the first layer is made of a wooden-
329 like isolation material commonly used; the second layer is made of a thick black isolation material (element 1)
330 which encloses the third layer. This third layer is composed of a copper heating resistance (element 2) to assure
331 the proportion of a uniform heat load sent to the sensor.

332



333

334 Figure 6. Calibration apparatus. On the left: (a) DC power supply 1, (b) support, (c) calorimeter, (d) DC power
335 supply 2, (e) PID temperature controller, and (f) measuring system and PC interface. On the right: (1) Thick
336 isolation layer, (2) heating resistance, (3) Capttec® heat flux sensor, (4) heat sink.

337

338 On the other side of the heating resistance are several straight lines. This side is in contact with the thick black
339 isolation material to reduce any eventual heat losses in a non-desire direction. Additionally, part of the thick black
340 isolation material is cut out to make space to fit the heating resistance, also to avoid any undesirable horizontal
341 heat losses. Also, in this third layer, is the heat flux meter to be calibrated or characterized which is in direct contact
342 with the heating resistance (see figure 6 left, element 3). The fourth layer corresponds to an aluminum block
343 enclose with wooden-like isolation material, which serves as a heat sink. This heat sink aide the heat dissipated
344 from the heating resistance and traversing the heat flux meter, to reduce any heat storage in the latter.

345 The calibration procedure is based on a stability criterion which is set by the user in the LabView interface.
346 This criterion corresponds to the desired standard deviation value on the electrical response (in volts) of the heat
347 flux sensor, when a constant heat flux is sent to the heat flux sensor. The latter is accomplished when a constant
348 voltage setpoint is applied to the heating resistance. When this stability criterion is reached, the system changes
349 the voltage applied to the heating resistance to the next voltage setpoint assigned, also set by the user.

350

351

352

353

354

2.1.1. Validation of the calibration procedure

355 The validation of the calibration procedure and apparatus was performed by calibrating a Captec heat flux
 356 sensors of known sensitivity value. The Captec heat flux sensor used here (5 x 5 x 0,05 cm) has a sensitivity value
 357 of 21,4 $\mu\text{V}/\text{W}\cdot\text{m}^{-2}$, as provided by the manufacturer.

358 The calibration procedure performed was the same as the one described here before. The voltage setpoints
 359 applied to the heating resistance are presented in table 1. Also, in this table, the resulting heat flux sent by the
 360 heating resistance is presented; this heat flux is calculated by using the surface area of Captec 0,0025 m^2 and the
 361 resulting electric current (I) along with the equation $q = V \cdot I/S$. In this case, a heating resistance of 4 x 4 cm^2
 362 (17,3 Ω) was used. It is worth mentioning that better sensitivity values (closer to the manufacturer's value) were
 363 encountered when using the surface area of Captec to calculate the heat flux, instead of that of the heating
 364 resistance. Using the former leads to a sensitivity value of 20,7 $\mu\text{V}/\text{W}\cdot\text{m}^{-2}$ which is at 3% close to the
 365 manufacturer's reported value. On the contrary, using the surface area of the heating resistance leads to a sensitivity
 366 value at 38% close to the manufacturer's reported value.

367

368 Table 1. Calibration results from validation with Captec® heat flux sensors and sensitivity values.

| Voltage setpoints | | Resulting Current | \bar{U} FGT | \bar{q} |
|-------------------|--|-------------------|---------------------------------------|----------------------------------|
| V [V] | | I [A] | [μV] | [$\text{W}\cdot\text{m}^{-2}$] |
| 0,5 | | 0,028 | 173 | 5,6 |
| 1 | | 0,055 | 456 | 22 |
| 1,5 | | 0,085 | 1066 | 51 |
| 2 | | 0,113 | 1857 | 90 |
| 2,5 | | 0,141 | 2932 | 141 |
| Tests | K [$\mu\text{V}/\text{W}\cdot\text{m}^{-2}$] | R ² | Stability criterion [μV] | Relative error [%] |
| 1 | 20,75 | 0,9993 | 1×10^{-6} | 3,1 |
| 2 | 20,55 | 0,9997 | “ | 4,0 |
| 3 | 20,86 | 0,9998 | “ | 2,5 |
| 4 | 20,24 | 0,9996 | “ | 5,4 |
| 5 | 20,66 | 0,9995 | 1×10^{-7} | 3,5 |
| 6 | 20,34 | 0,9995 | “ | 5,0 |

369

370 The Captec sensor electrical response (\bar{U} FGT) was plotted against the averaged heat flux applied (q), where after
 371 repeating the procedure various times, the resulting sensitivity values are presented in table 1. The sensitivity value
 372 was determined by fitting a linear regression model forced to cross the origin. Better fitting results are obtained
 373 when taking the average value (\bar{U}). From these results, the accuracy of the proposed calibration setup and
 374 procedure may be established as to be $4,0 \pm 1,0\%$.

375

376 2.1.2. Calibration of Peltier modules

377 Peltier modules ($3 \times 3 \times 0,48 \text{ cm}^3$ and $3 \times 3 \times 0,37 \text{ cm}^3$) were calibrated using the calibration apparatus and
 378 procedure described in §2.1, with a heating resistance of the same size as the modules. This procedure was
 379 performed several times to observe repeatability, where an average value for the sensitivity K was encountered to
 380 be $239 \mu\text{V}/\text{W}\cdot\text{m}^2$ for the $3 \times 3 \times 0,48 \text{ cm}^3$ module, and $109 \mu\text{V}/\text{W}\cdot\text{m}^2$ for the $3 \times 3 \times 0,37 \text{ cm}^3$ module (some results are
 381 presented in table 2). The uncertainty of the sensitivity value depends of various factors: The uncertainty of the
 382 measuring system ($0,3\%$ of reading + 1 digit μV), the power source ($0,01 \text{ V}$ and $0,001 \text{ A}$) or the heating resistance
 383 employed, the surface sensor ($1,2 \times 10^{-6} \text{ m}^2$). Also, the reported uncertainty value of sensitivity should account for
 384 the validation relative error presented at the end of the previous subsection.

385

386 Table 2. Calibration results for the TEM with a heating resistance size of $3 \times 3 \text{ cm}$.

| Tests | $K [\mu\text{V}/\text{W}\cdot\text{m}^2]$ ($3 \times 3 \times 0,48 \text{ cm}^3$) | R^2 | Stability criterion [μV] | $K [\mu\text{V}/\text{W}\cdot\text{m}^2]$ ($3 \times 3 \times 0,37 \text{ cm}^3$) | R^2 | Stability criterion [μV] |
|-------|--|--------|--|--|--------|--|
| 1 | 237 | 0,9997 | 1×10^{-15} | 108 | 0,9993 | 1×10^{-10} |
| 2 | 236 | 0,9997 | “ | 107 | 0,9999 | “ |
| 3 | 240 | 0,9994 | “ | 110 | 0,9998 | “ |
| 4 | 242 | 0,9996 | “ | 110 | 0,9987 | “ |

387

388 The calculation of the uncertainty in the sensitivity value K was performed by following the Constant Odds
 389 Combination (COC) method, presented in [23]. The sensitivity value can also be determined equation 1, where
 390 $q = VI/S$, giving $K = US/VI$. When applying the COC method to the latter, yields the uncertainty in the
 391 sensitivity δ_K :

392

393
$$\delta_k = \sqrt{\left(\frac{S}{V_I} \delta_U\right)^2 + \left(\frac{U}{V_I} \delta_S\right)^2 + \left(-\frac{US}{V_I^2} \delta_I\right)^2 + \left(-\frac{US}{V_I^2} \delta_V\right)^2} \quad [\mu\text{V}/\text{W}\cdot\text{m}^{-2}] \quad (7)$$

394

395 where δ_U , δ_S , δ_I , and δ_V , are the uncertainty values of the devices part of the calibration apparatus.

396 The resulting sensitivity value for Peltier modules are: $239 \pm 3 \mu\text{V}/\text{W}\cdot\text{m}^{-2}$ for the ones with dimensions $3 \times 3 \times 0,48$
 397 cm^3 , and $109 \pm 7 \mu\text{V}/\text{W}\cdot\text{m}^{-2}$ for the ones with dimensions $3 \times 3 \times 0,37 \text{ cm}^3$.

398 The uncertainty in the direct heat flux measurement from the sensors (δ_q), were also determined using the COC
 399 method applied to equation 1. The uncertainty of the heat flux measurement from Peltier modules was encountered
 400 to strongly depend on the current value of the heat flux measured: $0,5 \text{ W}\cdot\text{m}^{-2}$ between 0 to $20 \text{ W}\cdot\text{m}^{-2}$. A constant
 401 sensitivity value was admitted here for Peltier modules, since the thermoelectric properties do not significantly
 402 vary among the working temperatures of the experiments. Captec heat flux meters have an average uncertainty of
 403 $1,36 \text{ W}\cdot\text{m}^{-2}$ in a range of 0 to $30 \text{ W}\cdot\text{m}^{-2}$, and the type T thermocouple have a maximum uncertainty of $0,48^\circ\text{C}$.

404

405 **3. Validation of the use of TEM and the decoupling model**

406

407 **3.1 Estimation of convective and radiative heat exchanges**

408

409 **3.1.1. The measurement device**

410 Based on the experimental setup proposed by former researchers, the setup implemented here (called
 411 “measurement device”) consists of the following components (see figure 7):

- 412 a) A couple of one black and one shiny coated Peltier modules installed with a small separation between
 413 them, as to expose all their sides to the air. These sensors were properly placed onto the surface studied
 414 using a silicon-based thermal grease with thermal conductivity of $5 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$.
- 415 b) A type T thermocouple to measure the air temperature at 10 cm above the surface studied (without
 416 radiation shield).
- 417 c) A type T thermocouple inserted among the semiconductors elements of the module to measure the
 418 temperature of the surface studied. This thermocouple was coated with nail polish, for electrical
 419 insulation purposes, before inserting it into the modules.

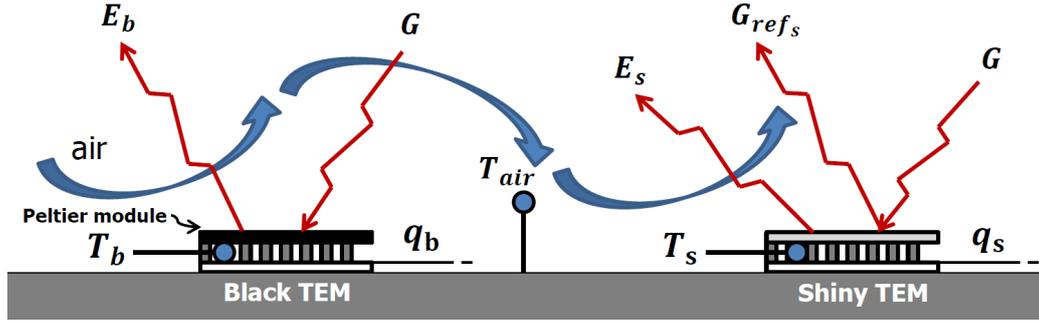


Figure 7. Representation of the convective and radiative heat exchanges over the measurement device.

3.1.2. Decoupling model for the convective and radiative heat exchanges

An analytical model is proposed here to distinguish the convective and radiative parts from the heat flux measurement. This model is based on a heat flux balance written for the considered surface i , as done by former researchers. A heat flux balance of the convective and radiative heat exchanges over this surface, as represented in figure 7, can be written for each black (b) and shiny (s) Peltier sensor, as follows:

$$q_b = q_{R_b} + q_{C_b} = \alpha_b G - \varepsilon_b \sigma T_b^4 + h_c \Delta T_b \quad [\text{W}\cdot\text{m}^{-2}] \quad (8)$$

$$q_s = q_{R_s} + q_{C_s} = \alpha_s G - \varepsilon_s \sigma T_s^4 + h_c \Delta T_s \quad [\text{W}\cdot\text{m}^{-2}] \quad (9)$$

where q represents the total heat flux entering or the absorbed heat flux by the surface, ε represents the thermal emissivity and σ represents the Stefan-Boltzmann constant. Together G , G_{ref_i} , and E , represent the net radiative heat exchanged between the surface and the surrounding environment (q_R); where G is the total incident radiation (short and long wavelength), G_{ref_i} is the reflected part of the total incident radiation, and E is the emitted radiation. The term $G - G_{ref_i}$ in equation 3 is equal to the absorbed part of the total incident radiation (G_{abs}), which can be written in terms of the thermal absorptivity (α) of the surface as $\alpha_i G$. The convective heat flux is represented by Fourier's law of convection, where h_c is the convective coefficient and ΔT_i is the temperature difference between the nearby air and the surface i . For the emitted radiation heat flux E , Stefan-Boltzmann's law of the radiation power emitted by a black body is considered, along with the assumption that each surface behaves as a gray surface.

443 Note here that until this moment, the total incident radiation G and the convective coefficient h_c are considered
 444 the same for all sensors among the measurement device. Then, by solving together equations 8 and 9, for G and
 445 h_c yields:

$$446 \quad G = \frac{\Delta T_b(q_s + \varepsilon_s \sigma T_s^4) - \Delta T_s(q_b + \varepsilon_b \sigma T_b^4)}{\alpha_s \Delta T_b - \alpha_b \Delta T_s} \quad [\text{W} \cdot \text{m}^{-2}] \quad (10)$$

447

$$448 \quad h_c = \frac{\alpha_s(q_b + \varepsilon_b \sigma T_b^4) - \alpha_b(q_s + \varepsilon_s \sigma T_s^4)}{\alpha_s \Delta T_b - \alpha_b \Delta T_s} \quad [\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}]. \quad (11)$$

449 Thus, by replacing equation 11 into Fourier's definition of convection for the shiny heat flux sensor presented in
 450 equation 9, the convective heat flux, yields:

451

$$452 \quad q_{C_s} = \left(\frac{\alpha_b \Delta T_s}{\alpha_b \Delta T_s - \alpha_s \Delta T_b} \right) q_s - \left(\frac{\alpha_s \Delta T_s}{\alpha_b \Delta T_s - \alpha_s \Delta T_b} \right) q_b + \frac{\Delta T_s \sigma (\alpha_b \varepsilon_s T_s^4 - \alpha_s \varepsilon_b T_b^4)}{\alpha_b \Delta T_s - \alpha_s \Delta T_b} \quad [\text{W} \cdot \text{m}^{-2}] \quad (12)$$

453

454 a similar expression is obtained for the convective heat flux for the black heat flux meter, just by replacing ΔT_s for
 455 ΔT_b . It can be inferred from equation 12 that assuming that the convective heat flux would be entirely determined
 456 by a heat flux meter coated with a shiny-foil, leads to an overestimation of this heat flux, and this, by considering
 457 only the radiative properties of the surface and the air-surface temperature difference of both sensors. In turn, this
 458 equation shows that the convective heat flux would be determined by the shiny heat flux meter only if: (i) both
 459 sensors would have the same temperature, (ii) the radiative properties of the shiny heat flux meter would have
 460 values of exactly zero, respectively. Note here that if the latter holds, the knowledge of the radiative properties of
 461 the black coating is not important which seems fairly straightforward to conceive because in such a case, a black
 462 heat flux would not be needed. If only item (i) holds, the convective component for both heat flux meters would
 463 be the same, and if in addition to this, (iii) the emissivity values is considered to be equal to the absorptivity values,
 464 i.e., a radiative environment where long wavelength heat radiation dominates at room temperature, the last term
 465 of equation 12 would be null and the convective heat flux would strongly depend on the emissivity values.

466 Nevertheless, equation 12 implies that the convective heat flux would be estimated then, without consideration
 467 of the surface morphology. For instants, if the morphology of the sensors, e.g., their thickness, which might
 468 considerably modify the relevant properties of the surface in which they are installed, then this would also yield
 469 into an overestimation of the convective heat flux.

470 Moreover, for surfaces of radiative properties similar to the black coating of the heat flux meter, an expression
 471 for the radiative component (q_{R_b}), can be obtained using the previous result, where q_{R_b} will result by subtracting
 472 q_{C_b} from q_b , which yields:

473

$$474 \quad q_{R_b} = q_b - \left[\frac{(\alpha_s - \alpha_b)\Delta T_b}{\alpha_s \Delta T_b - \alpha_b \Delta T_s} \right] q_s + \frac{\Delta T_b \sigma (\alpha_b \varepsilon_s T_s^4 - \alpha_s \varepsilon_b T_b^4)}{\alpha_s \Delta T_b - \alpha_b \Delta T_s} \quad [\text{W}\cdot\text{m}^{-2}]. \quad (13)$$

475

476 Note that from expression 13, if one were to have a shiny coating with perfect radiative properties (meaning that
 477 ε_s and α_s are equal to 0), one might assume that the value of the maximum net radiation heat exchange q_{R-b} would
 478 depend on the radiative properties of the black coating. However, in such a case, it can be shown with expression
 479 13 that the knowing of the radiative properties of the black coating becomes unnecessary when ε_s and α_s equal 0.
 480 In turn, the value of the net radiative heat exchange would depend on the value of ΔT_b and ΔT_s , in addition to the
 481 difference between q_b and q_s , resulting in: $q_{R_b} = q_b - \frac{\Delta T_b}{\Delta T_s} q_s$. Note here that the previous formulation do not treat
 482 the possible temperature modification that the heat flux sensors may introduced, this formulation only accounts
 483 for the difference between the black and shiny heat flux sensors.

484 A sensitivity analysis showed that the estimation of the convective (see eq. 12) and radiative (see eq. 13) heat
 485 fluxes is strongly influenced by the uncertainty in the emissivity values of the shiny coating, where a precise
 486 determination of the emissivity is required, with an uncertainty value around or smaller than 1×10^{-2} .

487 The emissivity values of both black and shiny coatings and the Captec surface were determined by following
 488 the procedure proposed on ISO 18434-1:2008(E). A black paint (NEXTEL Velvet Coating 811-21) with emissivity
 489 of 0,97 was used as the known-emissivity reference surface. The resulting emissivity values for each surface were:
 490 $0,953 \pm 0,012$ and $0,069 \pm 0,014$ for the black and shiny coatings, respectively. The emissivity value obtained for
 491 Captec heat flux meter was 0,12.

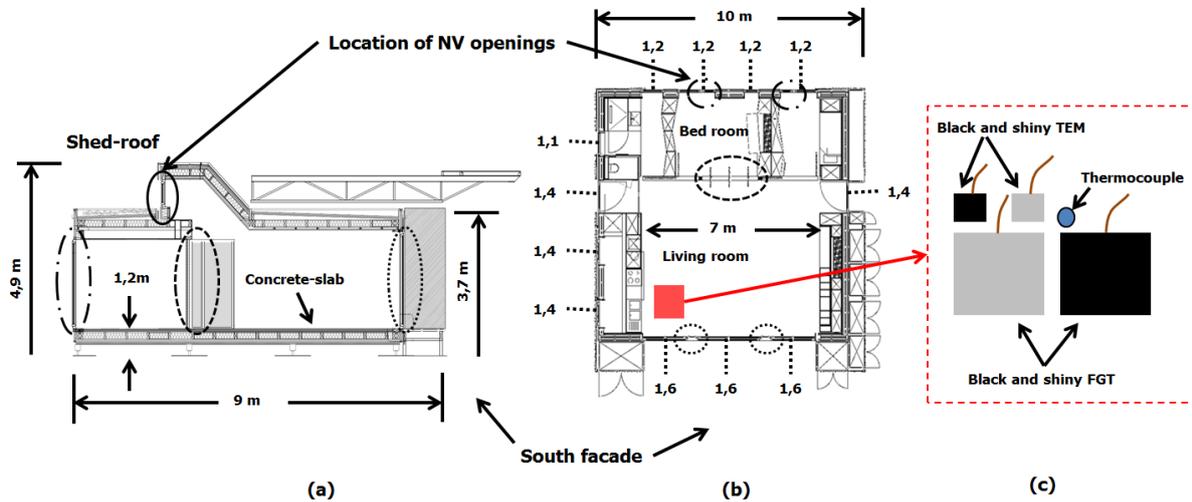
492

493 **3.2 Experimental study: Case of weak convective and radiative heat flux under in situ conditions**

494

495 An experimental study was conducted in a naturally ventilated Plus Energy House prototype (see figure 8) carried
 496 out during the summertime in 2016 in Southwest France. This study aimed to highlight the energy charge and
 497 discharge processes of a 68 mm thick concrete-slab located in the living room floor, which was submitted to
 498 different heat exchanges, resulting of the implementation of a configuration of the platform natural ventilation

499 automated system. Within this study, the proposed measurement device using TEM (see figure 7) was installed at
 500 one location on the concrete slab surface as shown in figure 8 (c) red square. Aside this measurement device, one
 501 black and one shiny FGT sensors were installed, to assure that the four sensors are submitted to the same
 502 conditions.



503 (a) (b) (c)
 504 Figure 8. Schematic of the architectural plan of the experimental platform: (a) West view, (b) top view, and (c)
 505 black-shiny couples of TEM and FGT.

507 As the only ongoing system of the PEH implemented in this study was the natural ventilation automated
 508 system, the experimental protocol implemented for the measurement campaigns during fall in November 2016,
 509 consisted of the following points: Experimental data were collected continuously, from 2/11 to 7/11, at a sampling
 510 rate of one minute, and from 18/11 to 21/11, at a sampling rate of five seconds. The solar shades were kept
 511 permanently closed during the measurement campaigns, and the natural ventilation openings were controlled
 512 manually. Only the openings at the south facade and the Shed-roof were functional; the openings at the north
 513 facade remained closed. The platform was unoccupied during the measurement campaigns, and the lights remained
 514 turned off. However, two computers remained operational; one for data collection and one for controlling the
 515 natural ventilation openings. Since the inside of the platform is divided into four zones: the living room, bedroom,
 516 bathroom, and toilet; all doors dividing these zones were kept opened.

517
 518 **3.3 Results and discussion**

519
 520 This section presents the experimental results obtained from the measurement campaigns described in §3.2 and
 521 a respective discussion. This section is organized as follows: All direct measurements, after calibration applied,

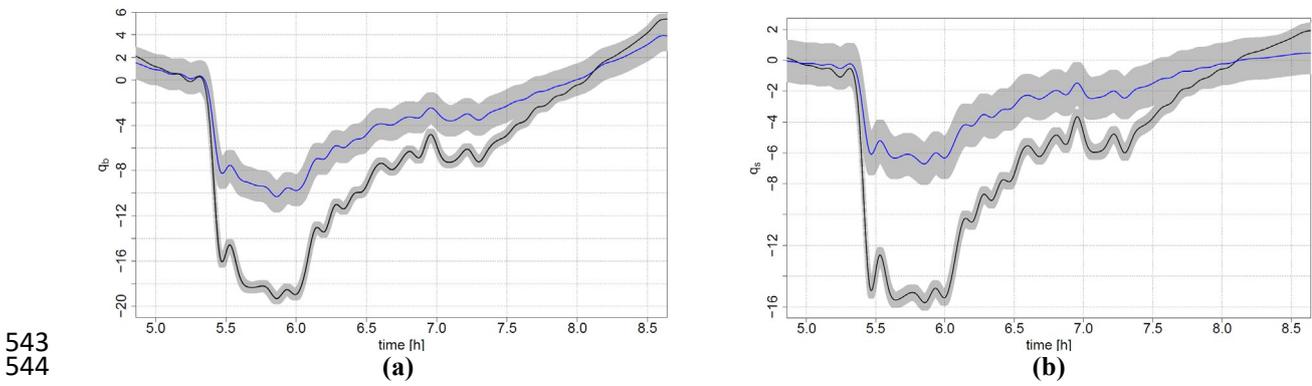
522 are first presented in a subsection §3.3.1 to evaluate any difference between TEM and FGT sensors; that is to say,
 523 the direct heat flux measurements from the black and shiny Peltier modules ($q_{b_{TEM}}$, $q_{s_{TEM}}$) and black and shiny
 524 Captec ($q_{b_{FGT}}$, $q_{s_{FGT}}$), respectively, and their temperatures (measured inside each sensor), along with the air
 525 temperature. This before is followed by §3.3.2, where the estimation of the convective and radiative heat fluxes
 526 using the results in §3.3.1, and equations 12 and 13 for TEM ($q_{b_{FGT}}$, $q_{s_{FGT}}$) and FGT ($q_{b_{FGT}}$, $q_{s_{FGT}}$). The distinction
 527 of whether they are calculated from TEM or FGT measurements is made through all these results. It should be
 528 noted that a positive heat flux value indicates a heat flux entering the surface in question. Conversely, a negative
 529 heat flux value indicates a heat flux leaving the surface. Only the moments where the natural ventilation openings
 530 were kept opened is shown in the graphs.

531

532 **3.3.1. Direct measurements from the heat flux meters: q_b , q_s , T_b , T_s , ΔT_s , ΔT_b**

533

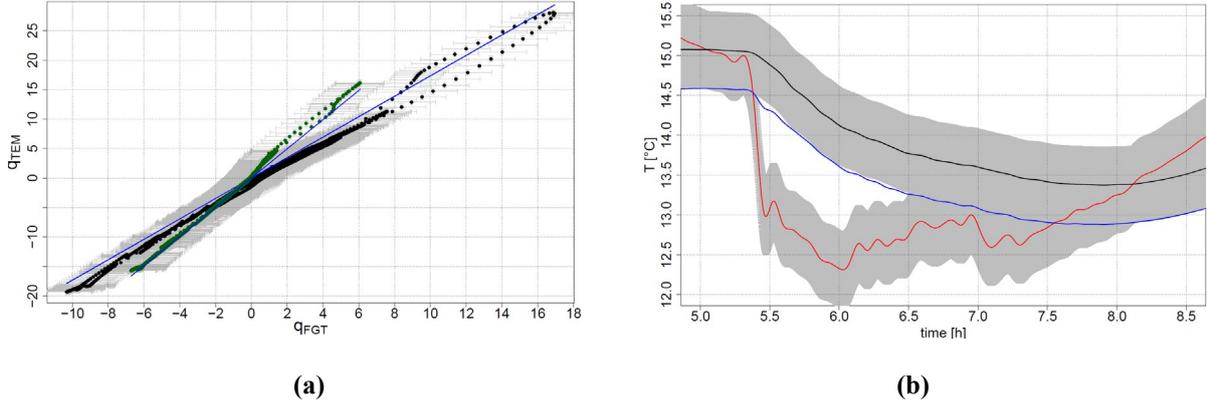
534 A significant difference can be observed in figure 9 between the heat flux measurement from the black TEM
 535 $q_{b_{TEM}}$ and FGT $q_{b_{FGT}}$ (a), and from the shiny TEM $q_{s_{TEM}}$ and FGT $q_{s_{FGT}}$ (b). Both heat fluxes measured by the
 536 TEM $q_{b_{TEM}}$ and $q_{s_{TEM}}$ (black lines) appears to be, at some points, significantly larger than the one measured by
 537 the FGT $q_{b_{FGT}}$ and $q_{s_{FGT}}$ (blue lines), specially when the natural ventilation openings are opened (gray regions).
 538 When plotting the heat flux measured by the TEM against the FGT (see figure 10 (a)), the straight line found
 539 indicates that the measurements from both TEM and FGT followed very similar behavior. Also, a linear regression
 540 model applied to these straight lines showed that the TEM measurement is about 2,5 times larger than the FGT
 541 measurement: $q_{s_{TEM}} = (2,5 + (+2/-1.6))q_{s_{FGT}}$, $R^2 = 0,9905$ for the shiny ones, and $q_{b_{TEM}} = 1,7q_{b_{FGT}}$, $R^2 =$
 542 $0,9758$ for the black ones.



543
544

545 Figure 9. Heat flux measurements from TEM (in black) and from FGT (in blue): (a) $q_{b_{TEM}}$ and $q_{b_{FGT}}$, and (b)

546 $q_{s_{TEM}}$ and $q_{s_{FGT}}$. Uncertainties are presented by the bands.



547
548

549 Figure 10. Heat flux measurements from TEM plotted against FGT: (a) $q_{b_{TEM}}$ and $q_{b_{FGT}}$ (black), and $q_{s_{TEM}}$ and
550 $q_{s_{FGT}}$ (green); (b) temperature measurements inside TEM (in black), inside FGT (in blue), and air (in red).

551
552
553

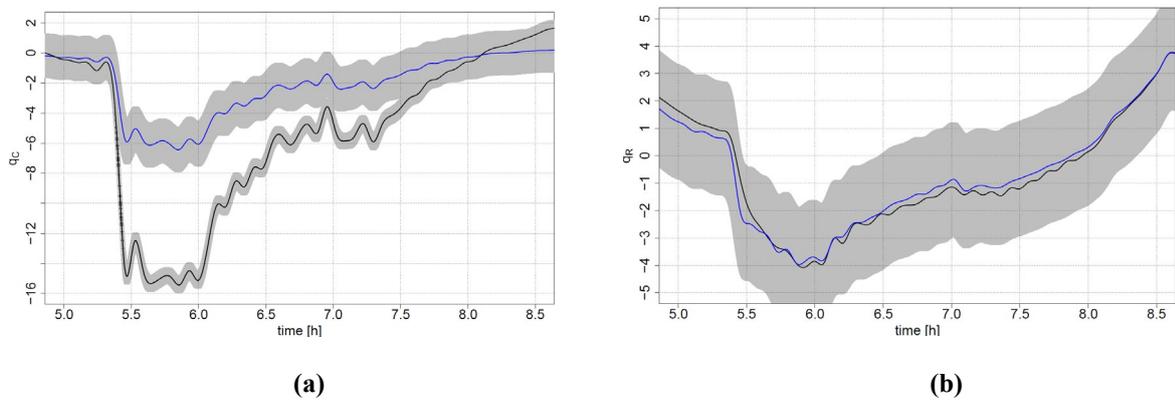
Moreover, figure 10 (b) shows that a difference is also encountered in the temperature measurements inside
554 the TEM and FGT. When the former and latter are plotted against each other, the linear regression model shows
555 that the difference is of approximately 0,5 °C. This difference might be associated with the calibration of the
556 thermocouples inside the TEM, since the temperature measurement connectors inside FGT were employed as
557 given by the manufacturer.

558

559 3.3.2. Convective and radiative heat flux: q_C, q_R

560

561 After using equations 12 and 13 to compute the convective and radiative heat flux separately from TEM and FGT
562 measurements presented previously, the difference encountered between the heat flux measurements of TEM and
563 FGT also persists in the estimation of the convective component, as shown in figure 11: $q_{C_{TEM}} = (2,5 +$
564 $(+2/-1,5))q_{C_{FGT}}$, $R^2 = 0,9779$, and $q_{R_{TEM}} = 1,1q_{R_{FGT}}$, $R^2 = 0,9936$.



565
566

567 Figure 11. Heat flux from TEM (in black) and FGT (in blue): (a) Convective, and (b) Radiative.

568 Despite both q_{CTEM} and q_{CFGT} were computed using equation 12, the strong similarity between figure 9 (b) and
569 figure 11 (a) in the heat flux value, is explained by the closeness to a zero emissivity value presented by the shiny
570 coating employed. In fact, it can be shown with equation 12 that the direct measurement from the shiny TEM will
571 get far from the estimated convective heat flux as the emissivity value of the shiny coating gets far from zero. On
572 the other hand, the difference between both convective heat fluxes q_{CTEM} and q_{CFGT} appears to be presented only
573 for a heat flux value lower than $-1 \text{ W}\cdot\text{m}^{-2}$ (not presented here). Within -1 and $0 \text{ W}\cdot\text{m}^{-2}$, the difference between both
574 TEM and FGT is not easy to be perceived when dividing q_{CTEM} by q_{CFGT} , due to a high scattering, as expected.

575 At the moment, it has been proven that there is clearly a difference between the direct heat flux measurements
576 q_{STEM} and q_{SFGT} . It appears that this difference strongly affect the estimation of the convective heat flux, but not
577 the radiative heat flux (see figure 11). Thus, the analysis of the estimated convective and radiative parts might lead
578 to explain the difference between q_{STEM} and q_{SFGT} .

579 Figure 11 (b) shows that the estimated radiative heat flux resulted to be weak, where the difference encountered
580 between q_{RTEM} and q_{RFGT} are somewhat undifferentiable when accounting the uncertainties. From these results, it
581 can be shown that in a weak radiative environment, the heat flux measurement of TEM and FGT is mainly a
582 consequence of the convective nature in the environment where the air being at a different temperature with respect
583 to the surface, provokes the discharging or cooling of the latter, as one can fairly expect. This before leads to
584 conclude that the difference between q_{STEM} and q_{SFGT} should be caused by the characteristics affecting the
585 convective heat transfer.

586 Before going further, led us analyze if the proposed calibration methodology influences the sensitivity value
587 of TEM, which may ultimately influence their heat flux measurement.

588

589 **3.4. Influence of the calibration method and the sensitivity value**

590

591 In §2.2.1 the proposed calibration method was shown to be in high correspondence with the sensitivity value
592 estimated for Captec heat flux sensors when comparing the value obtained by calibration and the value given by
593 the manufacturer. Yet, the calibration method was performed several times for each TEM, which presented very
594 similar values between tests, as shown in tables 2.

595 Here, several questions may arise regarding the different materials in each sensor (TEM and FGT), regarding
596 the modifications made to the TEM such as the addition of the silicon paste, and even regarding the size of the
597 heating resistance employed in the calibration method. It could be expected that if the difference encountered

598 between q_{STEM} and q_{SFGT} is entirely explained by a calibration issue, the necessary sensitivity value for TEMs
 599 might be around two times the current value obtained by calibration, so that their heat flux measurement yields to
 600 similar values as the FGTs.

601 However, by equating equation 1, it could be shown that a factor of two should be expected when comparing
 602 the TEM and FGT heat flux measurements:

603

$$604 \quad \frac{q_{TEM}}{q_{FGT}} = \frac{U_{TEM}/K_{TEM}}{U_{FGT}/K_{FGT}} = \frac{U_{TEM}/(239 \pm 3 \mu\text{V}/\text{W} \cdot \text{m}^{-2})}{U_{FGT}/(125 \pm 3,75 \mu\text{V}/\text{W} \cdot \text{m}^{-2})} = (0,523 \pm 0,017) \frac{U_{TEM}}{U_{FGT}} \quad (14)$$

605

606 Thus, after verifying and having confidence in the proposed calibration method, it is clear that the only way for
 607 the q_{TEM} to be equal to q_{FGT} is that the U_{TEM} and U_{FGT} must present different values. In fact, U_{TEM} should
 608 present a value of about two times greater than U_{FGT} . Also, from expression 14, it can be expected that both U_{TEM}
 609 and U_{FGT} should present the same value in order to encounter a factor of two when converting their electrical
 610 response into heat flux measurement.

611 When plotting both electrical responses, the linear regression model resulted in: $U_{STEM} = 4,8U_{SFGT}$, $R^2 =$
 612 $0,9905$ for the shiny ones, and $U_{bSTEM} = 3,24U_{bFGT}$, $R^2 = 0,9758$ for the black ones. The difference between the
 613 regression models obtained for the black and shiny sensors lays on the use of the exact sensitivity value of the
 614 FGT given by the manufacturer instead of the average value $125 \mu\text{V}/\text{W} \cdot \text{m}^{-2}$, where K_{bFGT} corresponds to 128
 615 $\mu\text{V}/\text{W} \cdot \text{m}^{-2}$ and K_{SFGT} corresponds to $123 \mu\text{V}/\text{W} \cdot \text{m}^{-2}$.

616 This before shows that the ratio of the electrical responses is indeed higher than the expected, and thus, the
 617 difference encountered between U_{STEM} and U_{SFGT} is entirely associated with the measurement of the TEMs, which
 618 turned out to be around 2,5 times too large.

619 At the moment, the previous analysis has shown that the electrical response of Peltier modules appears to be
 620 too large, as suggested by the analysis in §3.3, and that in this particular study, the convective part is the one
 621 affected.

622 Some of the causes that might be influencing the electrical response of Peltier modules can be inferred. First,
 623 a higher electrical response value should correspond to a higher temperature difference between the ceramic layer
 624 attached to the concrete surface and the one exposed to the air (in other words, a higher heat input). Since it is
 625 supposed here that both sensors TEM and FGT are exposed to the same convective and radiative conditions, e.g.,
 626 airspeed, air temperature, view factors, and that the radiative part has been proven to be weak and the same between

627 them, the morphology of the TEMs and the surface they are disposed might be the leading cause of the higher
628 electrical response.

629 The thickness of TEMs can enhance the convective coefficient around them, which might result in an enhanced
630 convective heat transfer causing the temperature of the surface in contact with the air to drop faster than the
631 temperature of the surface in contact with the concrete slab (analyzing the discharging case caused by the natural
632 ventilation scenario). If such a case is taking place, Peltier modules might be functioning as small fins (extended
633 surface), which might explained the enhancement of the convective heat flux with respect to FGT.

634 The materials employed in the fabrication of Peltier modules might also allow the module to store heat as it
635 converts the heat flux traversing it into an electric signal. The proposed calibration method has also revealed that
636 our TEMs present a capacitive electrical response with a time response of about one minute.

637 On the other hand, TEMs were disposed on a concrete surface during the measurement campaigns using a high
638 conductive thermal grease, but these modules were disposed on an aluminum surface during the calibration
639 method. The type of surface where the sensors are installed, i.e., heavyweight, lightweight or insulating, might
640 affect the sensors measurement depending on the effusivity characteristics of such surface. For instance, if the
641 surface where the sensors are installed has different effusivity value, the heat absorbed by this surface would not
642 be at the same rate the heat flux is traversing the sensor (as suggested by [12]). This might then cause the heat to
643 be stored somewhere between the sensor or at the sensor interface with the surface on which it is disposed. This
644 heat stored will heat up the entire module, causing its thermoelectric properties to inherit larger values. The
645 Seebeck coefficient of semiconductor materials, Bi_2Te_3 in this case, being more susceptible to a changing in
646 temperature than the thermal conductivity, might also provoke a higher electrical response. Also, the effect of
647 adding the silicon paste might contribute to the heat storage, increasing the average temperature of the module.

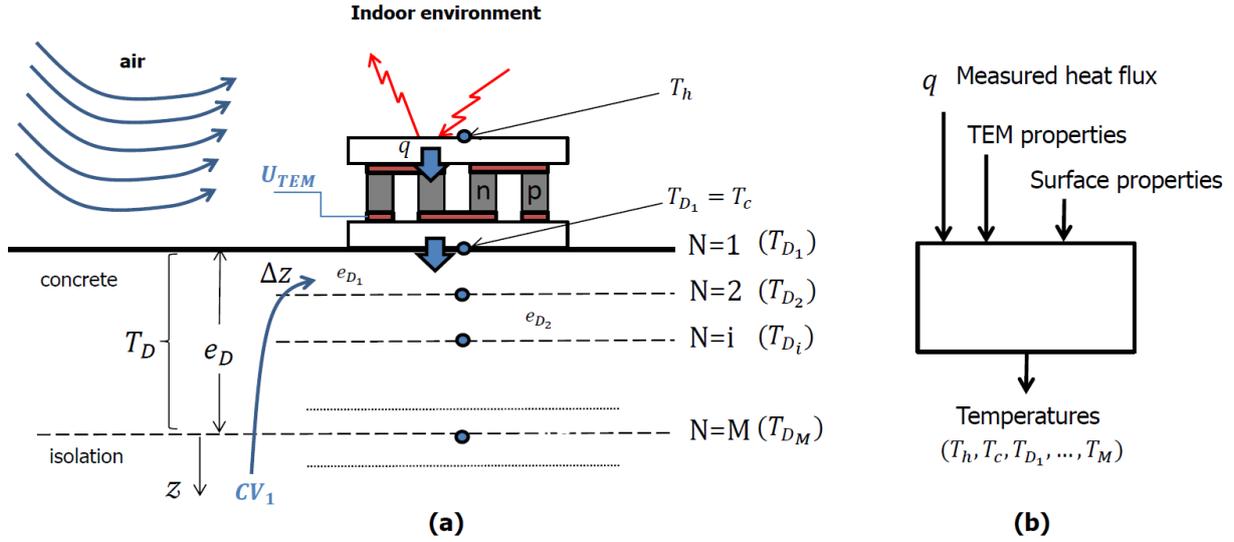
648 These three last remarks concerning the TEM thickness, the energy storage in the TEM and the effusivity of
649 the surface they are disposed, are boarded and analyzed in the following subsections.

650

651 **3.5. Influence of the heat storage and time response**

652

653 To analyze if the materials employed in the TEMs are of any influence in their heat flux measurement by the
654 possible heat stored in them, a discretized model for the concrete slab coupled with simple heat balances for the
655 TEM is introduced here (see figure 12).



656

657 Figure 12. Schematic coupled model for TEM and the surface they are disposed: (a) Domain modeling, and (b)
 658 inputs and outputs of the model.

659

660 First, a heat balance is written for each of the ceramic layers of the TEM, as follows:

661
$$\rho_{cer} c_{p_{cer}} e_{cer} \frac{dT_h}{dt} = q + \frac{\lambda_{TEM}}{e_{TEM}} (T_c - T_h) \quad (12a)$$

662
$$\rho_{cer} c_{p_{cer}} e_{cer} \frac{dT_c}{dt} = \frac{\lambda_{TEM}}{e_{TEM}} (T_h - T_c) + \frac{T_{D_1} - T_c}{R_{c,D-TEM}} \quad (12b)$$

663

664 where the subscript “cer” refers to the ceramic layer. The temperatures of each ceramic layer are respectively, T_h
 665 for the superior layer also referring to the “hot” layer, and T_c for the inferior layer which also refers to the “cold”
 666 layer. The heat stored in the superior ceramic layer should be equal to the heat flux entering the TEM at this layer
 667 represented as q , which in this case also represents the heat flux measurement, and the heat flux leaving the
 668 superior layer towards the inferior layer. The leaving heat flux is simple given by the temperature difference
 669 between the two ceramic layers times the equivalent thermal conductivity λ_{TEM} and thickness of the sensor e_{TEM} ,
 670 as proposed by [5]. The heat stored in the inferior ceramic layer is then given by the heat flux leaving the superior
 671 ceramic layer and the heat flux leaving the inferior ceramic layer by conduction to the concrete slab surface. The
 672 latter is represented by the temperature difference between the inferior ceramic layer and the surface temperature
 673 of the concrete slab T_{D_1} , divided by the thermal contact resistance between them $R_{c,D-TEM}$.

674 This model is attained when considering the following hypothesis:

- 675 1) The temperature of each ceramic layer is considered to be the same through the entire layer. This means
 676 that the superior ceramic layer is at the uniform temperature T_h .

677 2) The thermoelectric properties of the sensor correspond to equivalent properties, such as the thermal
678 conductivity λ_{TEM} , which corresponds to that of the sensor as a whole (see table 3). Here, this property
679 is estimated from the impulse method electrical response determined after the calibration apparatus and
680 fitting its response to a first order model.

681 3) The ceramic layers are the components materials with the most significant heat storage capacity.

682

683 Moreover, the conduction heat transfer through the concrete slab is modeled using the classic finite difference
684 discretization approach with heat storage:

685

$$686 \quad \rho_D c_{pD} \Delta z \frac{dT_{DN}}{dt} = \lambda_D \frac{T_{N-1} - 2T_N + T_{N+1}}{\Delta z} \quad (15a)$$

$$687 \quad \rho_D c_{pD} \Delta z \frac{dT_{D1}}{dt} = \frac{T_c - T_{D1}}{R_{c,D-TEM}} + \frac{\lambda_D (T_{D2} - T_{D1})}{\Delta z} \quad (15b)$$

$$688 \quad \rho_D c_{pD} \frac{\Delta z}{2} \frac{dT_{DM}}{dt} = \lambda_D \frac{T_{M-1} - T_M}{\Delta z} + 0 \quad (15c)$$

689

690 where “D” refers to the concrete slab, N to the number of node studied. Equation 15b presents the boundary
691 condition used at the superior node in contact with the inferior ceramic layer of the TEM. Finally, equation 15c
692 presents the boundary condition at the bottom node “M” of the concrete slab is considered to be isolated, where a
693 null heat flux is assigned.

694

695

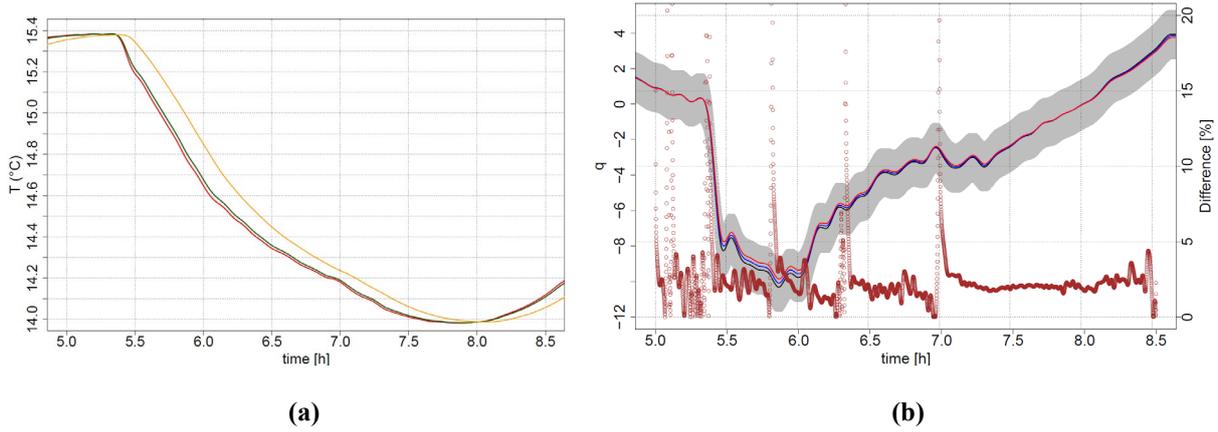
Table 3. Values of the model parameters.

| Parameters | Value | Parameters | Value |
|------------------|-------|------------------|--------------------|
| e_D [mm] | 68 | e_{cer} [mm] | 1 |
| M | 64 | e_{TEM} [mm] | 4,8 |
| Δz [mm] | 1,06 | λ_{TEM} | 1,6 |
| λ_D [24] | 1,8 | ρ_{cer} [5] | 3890 |
| ρ_D [24] | 2300 | c_{pcer} [5] | 880 |
| c_{pD} [24] | 1000 | $R_{c,D-TEM}$ | 1×10^{-4} |

696

697 Figure 13 shows the numerical results computed using the software R (library deSolve) with the Radau method
698 (implicit Runge-Kutta), with a time step of five seconds. In this case, assuming a heat flux input q as the

699 measurement given by the black FGT q_{bFGT} . These results show that the heat storage within the TEM can be
700 considered as no significant with respect to the heat stored in the concrete slab (see figure 13 (a)): 2,5 J for each
701 ceramic layer. The latter is drawn from the closeness between T_h , T_c , and T_{D_1} (superposed with T_c). Although a
702 difference in the heat flux given by the three terms on the right-hand side of equation 12 can be observed in figure
703 13 (b), still it can be considered as no significant since the relative error lays below 5%.
704



705
706 (a) (b)
707 Figure 13. Numerical results when the input q is q_{bFGT} . (a) Temperatures: T_h (red), T_c (dark red), T_{D_1} (green),
708 and T_{D_M} (orange). (b) Heat flux: q_{bFGT} (black), between T_h and T_c (blue), between T_c and T_{D_1} (red), and
709 relative error between black and blue.
710

711 3.6. Influence of the thickness difference

712 To analyze the influence of the thickness, both TEM and FGT are considered as extended surfaces (fins)
713 disposed over the concrete slab. Within the formulation of the heat conduction differential equation for the case
714 of a uniform cross section fin, is the geometrical factor f_g which groups the convective heat transfer coefficient
715 with no fin h_c , the perimeter of the fin, its thermal conductivity and its cross sectional area: $f_g = 2\sqrt{h_c/\lambda e}$.

716 When considering that the conduction heat transfer between the concrete slab and the sensor is equal to the
717 convective heat transfer at the surface of the sensor (the tip of the fin), the analytical solution of the fin equation
718 yields [25]:

$$719 \quad q = \frac{1}{S} \sqrt{h_c P \lambda S} \frac{\sinh(f_g e) + \frac{h_c}{f_g \lambda} \cosh(f_g e)}{\cosh(f_g e) + \frac{h_c}{f_g \lambda} \sinh(f_g e)} [T_s - T_{ia_s}] \quad [\text{W} \cdot \text{m}^{-2}] \quad (16)$$

720
721 where the coefficient h_c is enhanced by the factor: $\frac{1}{S} \sqrt{h_c P \lambda S} \left[\sinh(f_g e) + \frac{h_c}{f_g \lambda} \cosh(f_g e) \right] / \left[\cosh(f_g e) + \frac{h_c}{f_g \lambda} \sinh(f_g e) \right]$.

722 Therefore, by computing the ration q_{TEM}/q_{FGT} , the ratio of the enhancement of the convective heat flux by
 723 the TEM and FGT can be determined. Table 4 shows the results at different h_C values. The thermal conductivity
 724 of FGT employed here is $55,6 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, as computed from the value presented in [20] and the respective
 725 geometrical parameters.

726

727 Table 4. Geometrical factors for TEM and FGT at different h_C values.

| h_C | $f_{g_{TEM}}$ | $f_{g_{FGT}}$ | $f_{g_{TEM}}/f_{g_{FGT}}$ | q_{TEM}/q_{FGT} |
|-------|---------------|---------------|---------------------------|-------------------|
| 2 | 32,27 | 16,96 | 1,90 | 3,41 |
| 3 | 39,53 | 20,77 | " | 3,44 |
| 4 | 45,64 | 23,99 | " | 3,44 |
| 5 | 51,03 | 26,82 | " | 3,55 |
| 6 | 55,90 | 29,38 | " | 3,39 |

728

729 From table 4 it can be observed that the simple morphology of the TEM increases the heat transfer rate by
 730 convection with respect to the FGT, despite the value of the convective heat transfer coefficient (range of values
 731 chosen according to the working convective heat flux and temperatures results). In this table, second column from
 732 right to left, it can be seen that a factor of two should indeed be expected, merely by the difference between the
 733 geometrical parameters and the materials of the sensor.

734 Moreover, under the hypothesis of convective heat transfer only at the surface of the sensor (the end of the
 735 fin), which seems fairly straightforward since the length of the fin is smaller in this case with respect to the cross
 736 sectional area, a ratio of about 3,4 should rather be expected between the convective parts of both sensors. The
 737 latter seems to fall within the ratio encountered in §3.3.2, when accounting for the uncertainties. Thus, at the
 738 moment, all the analysis presented here before bring us to conclude that the leading cause of the difference between
 739 the measurements of TEM and FGT, might indeed be due to not only their geometrical properties but also to their
 740 thermal properties. This last remark bring us to propose a correction to the measurement of TEM when use as in
 741 the “measurement device.”

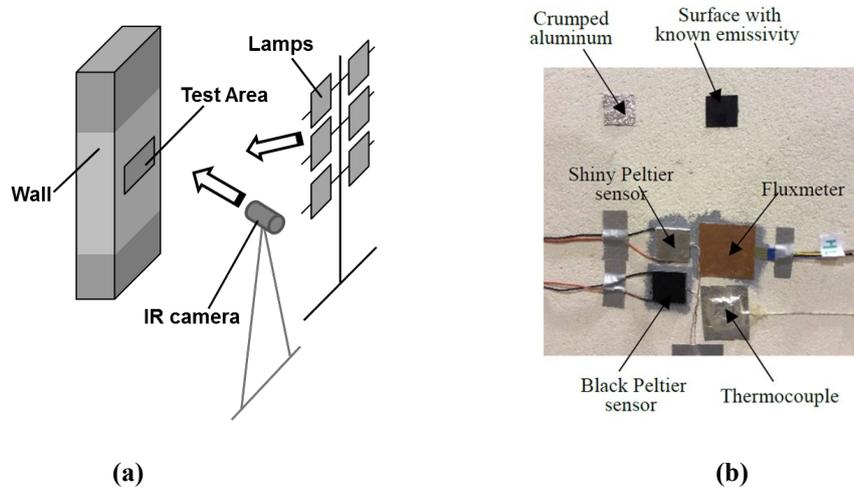
742 The following section is dedicated to test the proposed “measurement device” and decoupling model for
 743 estimating the convective and radiative parts in a strong heat flux environment.

744

745 **4. Application of the measurement device and the decoupling model: Case of strong radiative heat flux on**
746 **an external wall in controlled conditions**

747

748 The experiments were designed to characterize the thermal properties of a multilayer wall, placing the
749 “measurement device” on its front and rear faces, under laboratory conditions (see figure 16). In this study, apart
750 from the installation of the measurement device, a Captec heat flux sensor without coating (5x5 cm²) was installed
751 (see figure 16 (b)), merely as a reference. The emissivity of the latter is known. The wall structure is composed
752 of the following layers from the front face to the rear face: Mortar (1 cm), concrete (20 cm), insulation (4 cm), and
753 plaster (1,25 cm).



754

755

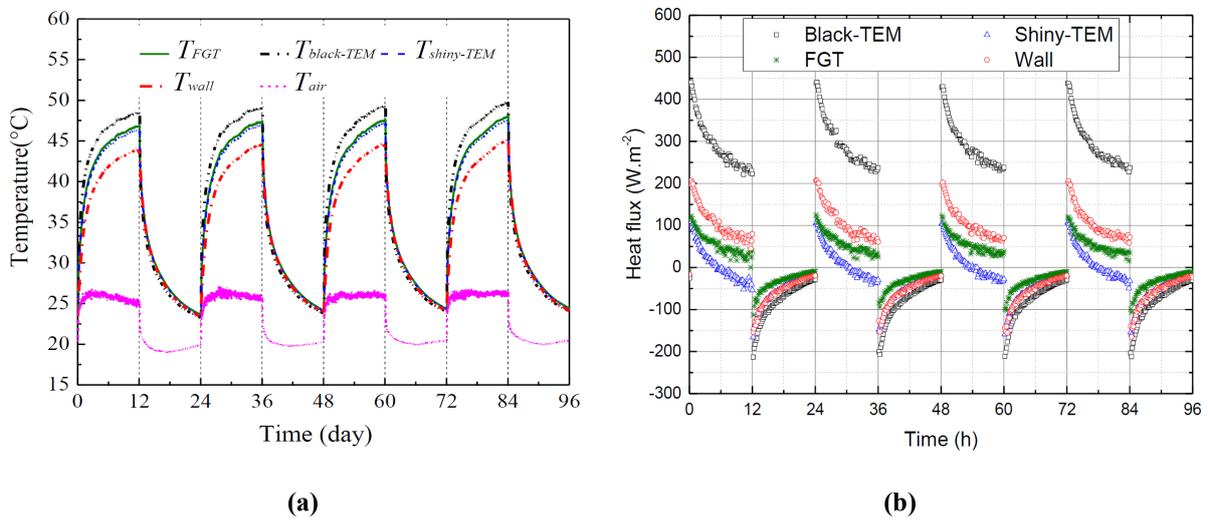
756 Figure 16. (a) Schematic of the experimental setup, and (b) the “measurement device” installed on the front face
757 of the wall.

758

759 The experimental protocol followed in this study consisted of heating the test area using a set of six halogen
760 lamps, with available radiation intensity from 0 to 1380 W·m⁻², by inducing a square-wave signal of 24 hours
761 period. This corresponds to a 12 hours heating or charge period followed by a 12 hours cooling or no charge period,
762 where the lamps were turned off. The majority of the emitted energy from the lamps (up to 85%) lies in the infrared
763 and near-infrared regions of the spectrum, with 15 - 20% falling into the visible (400 to 700 nm), and less than 1%
764 in the ultraviolet wavelengths (below 400 nm).

765 The resulting temperatures of each sensor in the test area are presented in figure 17 (a). Note here that the wall
766 surface temperature is measured by a thermocouple pasted at the wall surface using thermal silicon grease covered
767 with a shiny coating (see figure 16 (b)).

768 As expected, the black TEM presents the highest temperature value during the charge period and, despite the
 769 closeness of all temperatures during the no charge period, the black TEM also presents the lowest temperature
 770 value, due to radiative properties of its surface coating. For the shiny TEM and the FGT, it can be observed that
 771 despite their low emissivity, both heat flux meters heat up during the charge period, indicating that their
 772 absorptivity values may not be the same as their emissivity values, otherwise they might not heat up when the
 773 heating source has LWL nature only, according to Kirchhoff's law of radiation. As the nature of the lamps
 774 implemented here are of the halogen type (put wavelength range), the absorptivity values of the coatings were
 775 chosen from the literature, being 0,97, 0,15 for the black and shiny coatings respectively, and 0,65 for the wall
 776 surface [26,27].
 777



778 (a) 779 (b)
 780 Figure 17. For four consecutive charge and discharge periods: (a) Temperature results (b) Heat flux.

781
 782 The heat flux measurements from the black and shiny TEM, and from the FGT, are presented in figure 17 (b)
 783 for the four charge-discharge periods, along with the absorbed heat flux by the wall q_{wall} computed using
 784 equations 9 and 10. As expected during the charge period, the heat flux from the black TEM presents the higher
 785 values. The heat flux measurements from the shiny TEM and FGT are affected by the radiative properties of their
 786 coating surfaces as explained before. Figure 17 (b) clearly shows that, for the discharge periods, the absorbed heat
 787 flux can be well estimated by only using a shiny TEM, despite the large values of the convective heat flux
 788 encountered. Not as so for the charge period.

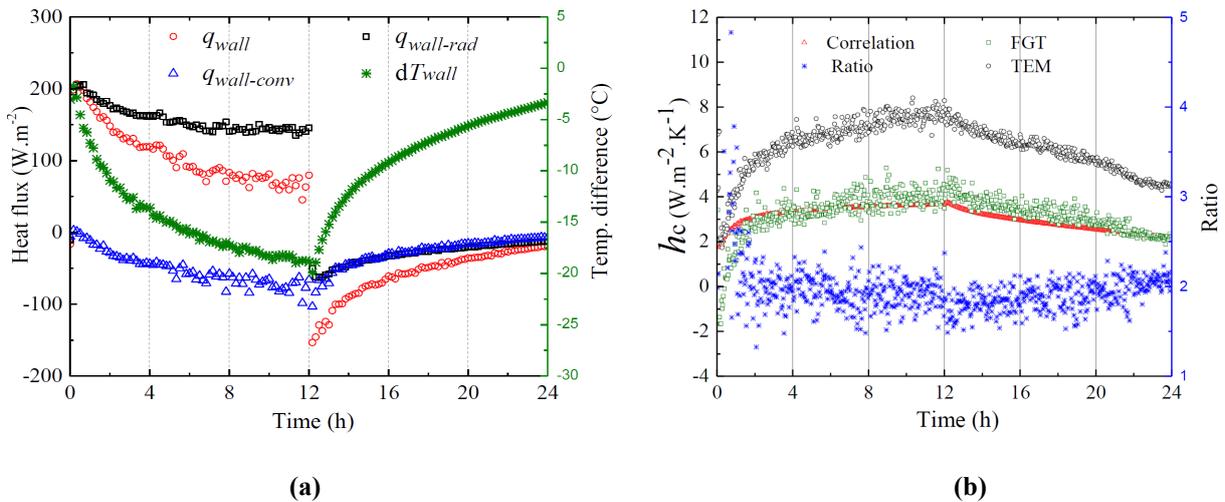
789 The decreasing behavior of the heat flux measurements of each heat flux meter can be explained by looking
 790 closely to the convective and radiative parts of the absorbed heat flux in the first charge-discharge period presented
 791 in figure 18 (a). During the charge period (0 - 12 h), for the convective component, the negative values indicates

792 that the test area is hotter than the surrounding air, which is fairly expected since the air temperature is always
 793 lower (see figure 17 (a)). This statement is also verified by the temperature difference in figure 18 (a).

794 Moreover, the decreasing behavior of the radiative component, presented also in figure 18 (a), might indicate
 795 that the test area is also cool down by radiation to the surrounding surfaces. During the discharge period (12 - 24
 796 h), as the wall and sensors seek thermal equilibrium, the heat released decreases over time reaching a heat flux
 797 value close to zero. Note here that the insulated properties of the wall first layer may also help to explain this
 798 behavior.

799 Figure 18 (b) shows the resulting convective heat transfer coefficient using equation 11 computed for the TEM
 800 and for the FGT, during the first charge-discharge period. In this figure the ratio of both coefficients is presented
 801 using blue asterisks with its axis on the right-hand side. Clearly a difference between both coefficients is observed,
 802 having a ratio value (around two). Moreover, the convective heat transfer coefficient was also calculated using a
 803 natural convection correlation for vertical plates [28] (small red triangles), also presented in figure 18. The latter
 804 proves once again that the FGT heat flux meter estimates well enough this convective coefficient, as expected.

805



806

807

808 Figure 18. For the first charge-discharge period: (a) Convective heat transfer coefficient, and (b) Absorbed heat
 809 flux and the convective and radiative parts.

810

811 5. Conclusions

812

813 An experimental investigation aiming to propose the use of Peltier modules as an alternative to conventional
 814 heat flux sensors for the estimation of the convective and radiative parts, was conducted in environments presenting
 815 weak and strong convective and radiative heat fluxes. The heat flux measurement from Peltier modules (TEM)

816 and conventional heat flux sensor (FGT) are compared and analyzed. Here, commercial heat flux sensors Captec®
 817 were used as conventional heat flux sensors, since as reported in the literature, their performance in the heat flux
 818 measurement has been proven to largely acceptable.

819 The comparison was first made in the weak heat flux environment, which consisted of a full-scale naturally
 820 ventilated positive energy house prototype, named Sumbiosi, located in Southwest France. For this, a
 821 “measurement device” consisting of a couple of black and shiny Peltier modules and three thermocouples, along
 822 with a simple model for decoupling the convective and radiative parts, are proposed here.

823 When estimating the convective part separately using the measurements from TEM and FGT, a difference
 824 between both measurements appears repeatedly for both cases of weak and strong heat fluxes. Three plausible
 825 causes for this difference were investigated in order to give a verified explanation: The influence of the calibration
 826 methodology implemented to find the sensitivity K of TEM, the morphology of TEM such as the thickness, and
 827 the heat storage regarding the materials employed in the TEM.

828 As it was found, the leading cause of the difference between the measurement of TEM and FGT, lays in
 829 the geometrical and thermal properties of the sensors. The latter was encountered when treating the sensors as
 830 extended surfaces, which showed that the difference in the measurements is expected to be encountered despite
 831 the value of the convective heat transfer coefficient.

832

833 Nomenclature

834 Latin letters

| | | |
|-------|--------------------------------------|--------------------------------|
| q | Heat flux | $W \cdot m^{-2}$ |
| S | Surface area | m^2 |
| G | Total incident radiation heat flux | $W \cdot m^{-2}$ |
| h_c | Convective heat transfer coefficient | $W \cdot m^{-2}$ |
| K | Sensitivity value | $\mu V \cdot m^2 \cdot W^{-1}$ |
| N | Number of thermoelectric couples | — |
| U | Electrical response | μV |
| e | Thickness | m |
| a | Seebeck coefficient | $\mu V \cdot K^{-1}$ |
| GF | Geometrical factor for TEM | m |
| f_g | Geometrical factor for fins | — |
| Re | Electrical resistance | Ω |
| r | Electrical resistivity | |
| T | Temperature | $^{\circ}C$ |
| c_p | Specific heat capacity | $J \cdot kg^{-1} \cdot K^{-1}$ |
| V | Tension applied | V |
| I | Electrical current | A |
| E | Emitted radiation heat flux | $W \cdot m^{-2}$ |

835

836 Greek letters

| | | |
|-----------|----------------------|-------------------------------|
| λ | Thermal conductivity | $W \cdot m^{-1} \cdot K^{-1}$ |
| ρ | Density | $kg \cdot m^{-3}$ |
| δ | Uncertainty | |

| | | |
|---------------|---------------------------|-------------------------------|
| ε | Thermal emissivity | — |
| α | Thermal absorptivity | — |
| Δ | Refers to difference | |
| σ | Stefan-Boltzmann constant | $W \cdot m^{-2} \cdot K^{-4}$ |

837

838 **Subscripts and superscripts**

| | |
|----------------|------------------------|
| <i>eq</i> | Equivalent |
| <i>element</i> | Semiconductor elements |
| <i>i</i> | Surface studied |
| <i>C</i> | Refers to convective |
| <i>R</i> | Refers to radiative |
| <i>s</i> | Shiny coating |
| <i>b</i> | Black coating |
| <i>air</i> | Refers to air |
| <i>surr</i> | Refers to surroundings |
| <i>ref</i> | Refers to reflected |

839

840 **Acronyms**

| | |
|-----|---|
| FGT | Refers to conventional heat flux sensor |
| TEM | Refers to Peltier module |

841

842

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