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Design and experimental evaluation of a parabolic-trough Concentrating Photovoltaic/Thermal (CPVT) system with high-efficiency cooling.

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Abstract. The design and performance evaluation of a novel parabolic-trough concentrating photovoltaic/thermal (CPVT) system are discussed in the present study. Initially, the system design and manufacturing procedures as well as the characteristics of the system sub-components are thoroughly illustrated. At a second stage, the findings in regard to the optical quality of the parabolic trough are presented, as obtained through an experimental procedure that utilizes a custom-made measuring device. The device bears a grid of sensors (photodiodes), so that the irradiation distribution on the receiver surface and the achieved concentration ratio can be determined. Besides, the main factors that have a significant effect on the trough optical quality were identified through ray-tracing simulations. The system electrical and thermal performance was subsequently evaluated in a test rig specially developed for that reason. Three variations of the system receiver incorporating different PV-module and heat-sink designs were evaluated and the prototype CPVT system was found to achieve an overall efficiency approximately equal to 50% (44% thermal and 6% electrical efficiencies, respectively) with a very weak dependency on the operating temperature.

Keywords: optical analysis, ray-tracing, experimental evaluation, parabolic trough, CPVT system

Nomenclature

CR	concentration ratio
C_p	specific heat, J/kgK
G	solar radiation flux, W/m ²
H	height, m
I	electric current, A
k	thermal conductivity, W/mK
L	length, m
\dot{m}	mass flow rate, kg/s
P_{el}	electrical power, W
Q_{th}	thermal power, W
S	length of distortion segment, m
T	temperature, K
U	uncertainty associated with a value
U_0	thermal losses coefficient, W/m ² K
t_s	solid substrate thickness, m
W	width, m
V	electric voltage, V

55	\dot{V}_{tot}	volumetric flow rate
56		
57	Greek symbols	
58		
59	β	cell temperature coefficient, %/K
60	γ	receiver intercept factor
61	η_{el}	electrical efficiency
62	η_{th}	thermal efficiency
63	η_{tot}	total efficiency
64	η_0	optical efficiency
65	θ	incidence angle, °
66	ρ	reflectance
67	τ	transmittance
68		
69	Subscripts/Abbreviations	
70		
71	a	aperture, ambient
72	alpha	absorption coefficient
73	ave	average
74	b	beam
75	ch	channel
76	CR	concentration ratio
77	d	diffuse
78	el	electrical
79	EVA	ethylene-vinyl acetate
80	f	fluid
81	in	inlet
82	ins	insulation
83	max	maximum
84	min	minimum
85	out	outlet
86	PV	photovoltaic
87	MPP	maximum power point
88	ref	reference
89	refl	reflector
90	spec	specular
91	scat	scattered
92	th	thermal
93	tot	total
94	t	tape
95	w	wall

96

97 **1. Introduction**

98

99 The integration of an active cooling system into the receiver of a concentrating photovoltaic
100 (CPV) system, apart from increasing the system electrical efficiency, makes the surplus heat
101 available for utilization in other applications, where heat at temperatures in the range 60-80°C
102 can be exploited, such as water and space heating, (adsorption or desiccant) cooling [1,2] or
103 even desalination through membrane distillation [3,4]. The additional useful, thermal-power
104 output leads to a significant increase of the system overall efficiency, while the reduced, in
105 comparison to a flat-plate solar thermal collector, receiver dimensions render heat losses
106 limited, an additional beneficial feature in terms of system overall efficiency.

107 Cooling is a major concern regarding the design of concentrating photovoltaics, as the
108 integration of a heat dissipating configuration can have a beneficial impact on the system
109 electrical efficiency. A wide variety of cooling configurations that could potentially be suited
110 for the cooling of solar cells are presented in the review articles by Du et al. [5] and Royne et

111 al. [6]. Besides, Micheli et al. [7] focused on the cooling options for concentrating
112 photovoltaics that are made available through micro and nano-technology, such as micro-fins
113 (or micro-channels) configurations, micro heat pipes and the use of carbon nanotube
114 suspension as cooling fluid. Royne and Dey [8] proposed an active cooling system for densely
115 packed cells comprising a grid of impinging jets. An optimization methodology, based on
116 analytical models, was formulated in order to determine the layout and geometrical
117 parameters of the cooling nozzles that maximize the cell electrical output. Barrau et al. [9]
118 proposed a hybrid device that combines the techniques of impingement jets and
119 microchannel-flow for cooling a dense array of solar cells under high concentration. Rahimi
120 et al. [10] experimentally evaluated the performance of a water-cooled silicon cell module.
121 Indoor testing using a solar simulator of 1000 W/m^2 showed that the cell power output
122 increased by 30%.

123 The alternative technique of directly immersing a properly insulated PV module into the
124 cooling fluid has also been examined. Han et al [11] conducted a comparative study in terms
125 of optical transmittance and cooling capacity, in order to evaluate the applicability of different
126 fluids for immersion cooling. Besides, Zhu et al. [12] experimentally investigated the cooling
127 effectiveness of direct immersion of a solar cell module under concentrated sunlight
128 ($\text{CR}=160\text{-}200$) into a liquid.

129 Few examples of integrated CPVT systems can be found in the open literature. Early
130 studies by Chenlo and Cid [13] and Gibart [14] outlined the manufacturing procedure for
131 prototype linear CPVT systems based on the Fresnel lens and the parabolic reflector
132 technologies, respectively. Rectangular ducts were used to extract surplus heat in both studies.
133 Coventry [15] designed and manufactured a parabolic trough linear CPVT system with a
134 geometrical concentration ratio equal to 37. The receiver comprised an array of custom
135 designed mono-crystalline silicon cells cooled by water flowing inside an aluminium tube.
136 The system achieved thermal and electrical performance equal to 58% and 11%, respectively,
137 for mass flow rates in the range $37.5\text{-}42.5 \text{ mL/s}$. Li et al. [16] evaluated the overall
138 performance of a 2m^2 prototype linear CPVT system, which used a parabolic reflector to
139 concentrate solar radiation up to 31 suns. Three different types of cells (monocrystalline
140 silicon, “super cells” and GaAs) were tested. The heat sink used for the cooling of the cell
141 array was similar to that reported in [15]. The system employing the GaAs cell array obtained
142 a maximum overall efficiency of 50.6%, with 41.7% and 8.9% attributed to the thermal and
143 electrical efficiency, respectively.

144 Yongfeng et al. [17] performed a separate experimental evaluation for a variation of the
145 system investigated in [16], which achieves a concentration of 10x. The measured efficiency
146 of the GaAs cells was 9.5% and the thermal efficiency of the system was 34%. Rossel et al.
147 [18] manufactured a two-axis tracking 11x CPVT system. The system had an overall aperture
148 area of 3.6 m^2 and employed Fresnel reflectors to concentrate irradiation onto a silicon cell
149 module thermally bonded to a water cooled channel. The daily thermal efficiency of the
150 system, without electricity production, was measured higher than 60%. Vivar et al. [19] report
151 the performance evaluation of a Fresnel reflector linear system with concentration ratio 20x.
152 A module of the system resembles a fully sealed case, which encloses two arrays of Fresnel
153 reflectors that concentrate irradiation on two “micro-receivers” consisting of an array of
154 silicon solar cells bonded to cylindrical tubes. Daily measurements established an average
155 overall efficiency of 58% (50% thermal-8% electrical).

156 Chemisana et al. [20] proposed a design for a CPVT system that utilizes a linear Fresnel
157 lens and a CPC (compound parabolic concentrator) as primary and secondary concentrators
158 respectively. The system achieved a maximum concentration of 10x. A typical rectangular
159 channel served as the cooling device with water flow inside it under laminar flow conditions.
160 A 25x Fresnel lens linear CPVT system was integrated into a greenhouse as reported by

161 Sonneveld et al. [21]. Fresnel lenses were mounted onto the top glazing of the green house
162 and concentrated the solar irradiation on tracking hollow beams, which were supported by the
163 steel frame of the green house. Silicon solar cells were thermally bonded on the beams and
164 water was circulated through them. Daily performance measurements showed an overall
165 efficiency of 67% (56% thermal and 11% electrical). Nevertheless, the system optical losses
166 (equal to 30%) were excluded from the calculation of the efficiency.

167 Chaabane et al. [22] manufactured a linear CPVT system that comprised an asymmetric
168 compound parabolic reflector and a mono-crystalline silicon solar-cell module thermally
169 bonded to a rectangular duct. The performance evaluation of the system showed that the
170 maximum obtained thermal and electrical efficiencies were equal to 16% and 10%,
171 respectively. Du et al. [23] evaluated the performance of an 8x linear Fresnel reflector system.
172 At the system receiver, a silicon-cell module was bonded to a tube-on-plate heat sink with a
173 U-shaped tube. Hourly measurements illustrated that the system thermal and electrical
174 efficiencies under steady state conditions were approximately equal to 39% and 8% for
175 coolant flow rates larger than 0.035 kg/s. Kribus et al. [24] proposed a miniature point-focus
176 system with aperture area less than 1m^2 that used a dish concentrator and high-efficiency,
177 triple-junction cells operating at concentration of 500 suns. Nevertheless, although the system
178 was reported to be under construction, experimental data of the system actual performance
179 have not been published yet.

180 The evaluation of low-concentration, static CPVT systems has also been reported by a
181 number of researchers. Kong et al. [25] manufactured a low concentration static linear CPVT
182 system that employs a Fresnel lens and flat reflectors, as primary and secondary concentrators
183 respectively, with a geometrical concentration ration of 5.7. For a single daily measurement,
184 the system was reported to achieve peak electrical and thermal efficiencies equal to 10% and
185 56%, respectively. Brogren et al. [26] discussed the optical properties of the main components
186 (reflector, glazing cells) comprising a 4x compound parabolic concentrator photovoltaic
187 thermal system. The system optical efficiency was measured to be equal to 71%, while the
188 system electrical and thermal output were measured equal to $330\text{W}/\text{m}^2\cdot\text{cell area}$ and
189 $2300\text{W}/\text{m}^2\cdot\text{cell area}$, respectively.

190 Nilsson et al. [27] focused on the annual performance of a static photovoltaic-thermal
191 system employing asymmetrical parabolic concentrators. The annual electrical yield of the
192 system was estimated at $373\text{ kWh}/\text{m}^2$ cell area, while the thermal yield was $145\text{ kWh}/\text{m}^2$
193 glazed area. Bernardo et al. [28] experimentally evaluated the performance of a low-
194 concentrating parabolic CPVT system ($\text{CR}=7.8$). From a thermal performance point of view,
195 the optical efficiency and the heat-loss coefficient of the system were measured equal to 45%
196 and $1.9\text{ W}/\text{K}\cdot\text{m}^2$, respectively. The maximum electrical efficiency was 6.4%. Künemeyer et
197 al. [29] manufactured a static, low-concentration, V-trough CPVT module comprising four
198 arrays of polycrystalline cells cooled by water flowing inside channels formed by the
199 corrugated reflector frame. The overall efficiency of the system was in the order of 30%.

200 A novel linear Concentrating Photovoltaic Thermal (CPVT) system employing specially
201 designed monocrystalline solar cells and microchannel cooling devices is evaluated in the
202 present study. The main objectives of the study are to illustrate the design procedure and to
203 highlight all the technical challenges associated with the development of a novel, linear-focus
204 CPVT system and furthermore to experimentally evaluate the optical, electrical and thermal
205 efficiencies achieved by the system. Furthermore, the present investigation constitutes a
206 proof-of-concept study of the successful integration of two novel heat-sink configurations
207 developed [30-33] in a prototype CPVT system. Three different system receiver
208 configurations were considered employing different PV modules and cooling devices of
209 different design layouts. In the subsequent sections, the technical specifications and
210 geometrical parameters of the prototype system and its corresponding sub-components are

211 first presented, followed by the analysis of the system optical quality and the experimental
212 evaluation of the system electrical and thermal efficiency.

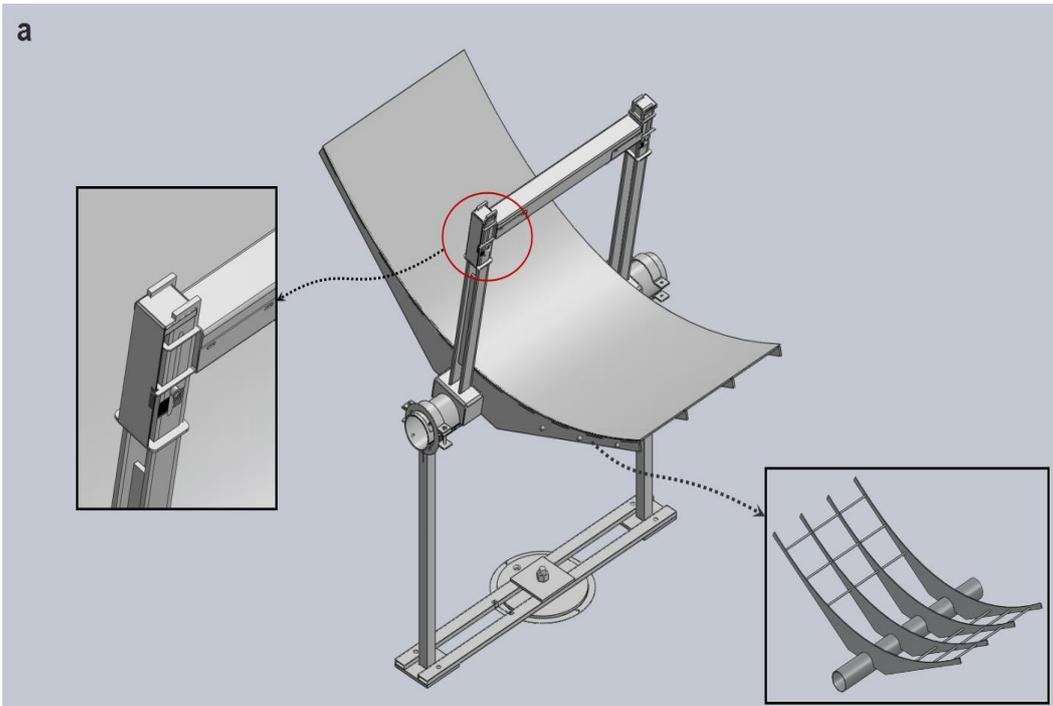
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215 2. Design and manufacturing of the prototype CPVT system

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217 A rigid metallic structure that realizes the parabolic shape of the reflector and supports the
218 receiver at the focal spot has been designed using three-dimensional CAD software (**Fig. 1a**)
219 and manufactured (**Fig. 1b**). The structure comprises the frame, onto which the reflecting
220 sheet and the receiver are seated, and the supporting arrangement, consisting of pillars and a
221 circular base that is bolted to the ground. The reflector sheet is bolted on the parabolic profile
222 of the frame, whereas the mounting of the receiver housing allows its translational
223 displacement along the frame brackets, with its final position fixed using screw-nut
224 assemblies. The parabolic profile is supported through metallic ribs mounted on the frame
225 main axle. The supporting arrangement also comprises two axle joints, namely the joint
226 between the main shaft and the supporting pillars and the rotating base discernable at the
227 lower part of **Fig. 1a**. Hence, the frame can rotate around both the horizontal and vertical axes
228 and thus two-axis tracking of the solar movement is possible. The parabolic frame realizes a
229 concentrator with overall aperture area of 2.0 m^2 (active area of 1.0 m^2) and a focal length of
230 690 mm . The parabola width and height are equal to 2.0 m and 0.362 m , respectively, while
231 its rim angle is equal to 71.9° . Since the width of the parabolic frame is equal to 2.0m , the
232 CPVT system active and overall aperture areas result equal to 1.0 and 2.0m^2 , respectively, due
233 to the fact that the active length of the PV module is equal to 0.5m , however the overall length
234 of the receiver has been extended to 1.0m . This has been done, in order to mitigate end effects
235 during the morning and afternoon hours, in the case that single-axis tracking was also
236 considered and furthermore to accommodate the tubing and wiring required within the
237 receiver. The frame was constructed of aluminum in order to make it lightweight and hence
238 facilitate the collector tracking.

239



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Fig. 1 Metallic structure of the CPVT system: (a) CAD drawing and (b) constructed frame.

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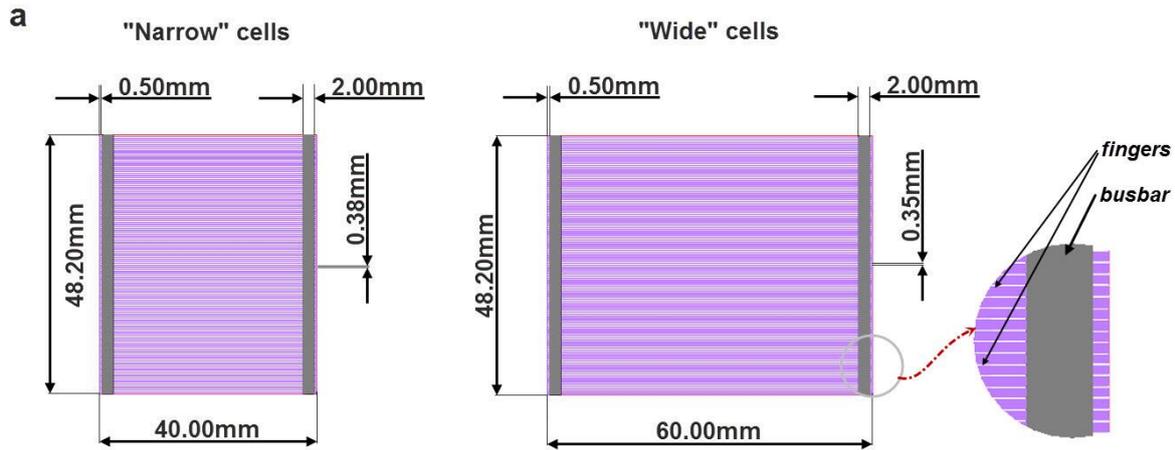
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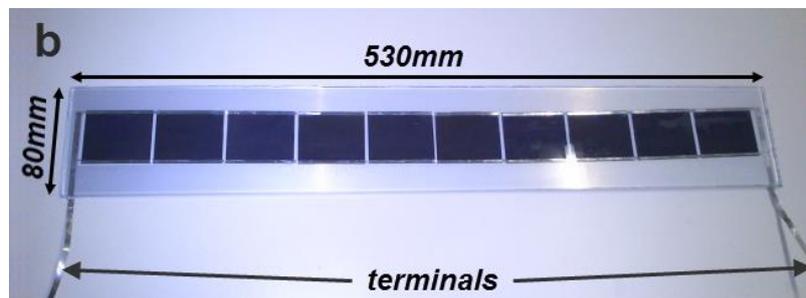
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Commercially available anodized aluminum sheets (MIRO high-reflective 95) by *Alanod Solar* were used as reflectors. The sheets specular reflectance is approximately equal to 92% [34]. Custom solar cells were developed by *Narec Ltd.* The cells were manufactured by monocrystalline silicon wafers of thickness equal to 150 μm and the most pronounced difference in their design, compared to conventional cells, is the much higher finger density, as depicted in **Fig. 2a**. In general mono-crystalline solar cells achieve higher efficiencies than polycrystalline and thin-film cells [35], while they have also been proven as more well suited for concentrating applications of moderate concentration ratio ($20 < \text{CR} < 100$) [15, 17, 28] than multi-junction III-V cells that require high concentration ratios ($\text{CR} > 200$) [36], in order to perform efficiently.

Two cell designs were considered having widths of 40.0 mm (“narrow” cells) and 60.0mm (“wide” cells), respectively. The 60.0mm width was dictated by the active width of the employed cooling devices. The additional cell design having width of 40.0mm was considered, in order to examine the effect of the extent of the mismatch between the cell and solar band widths on the PV module electrical performance. The basic dimensions of the solar cells are shown in **Fig. 2b** and the most pronounced difference compared to a conventional solar cell is the high finger density of the cell front electrical contact. The front contact was optimized by *Narec Ltd.*, which provided the cells, as a compromise between the capability of the cells to handle increased current density due to the concentrated irradiation and the reduction of their active area, since fingers, as metallic surfaces, are highly reflective. The optimization methodology produced the finger arrangement that maximized the cell efficiency. Ten cells were interconnected in series to fabricate a PV module, which comprises a front cover made of low-iron glass, the PV laminate (EVA and solar cells) and a back aluminum substrate. The cells were thermally bonded to the substrate using a thermally conductive, yet electrically insulating, adhesive tape ($k_t = 0.6 \text{ W/mK}$).



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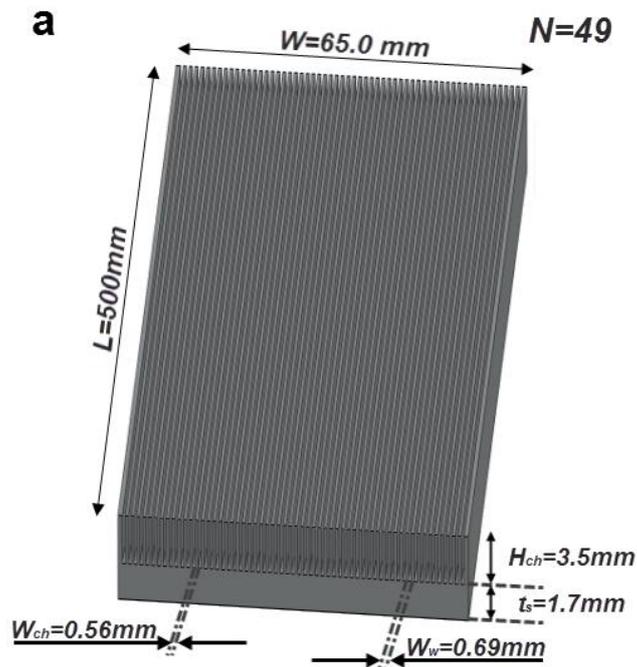
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Fig. 2 (a) Basic design parameters of the solar cells. (b) The assembled PV module.

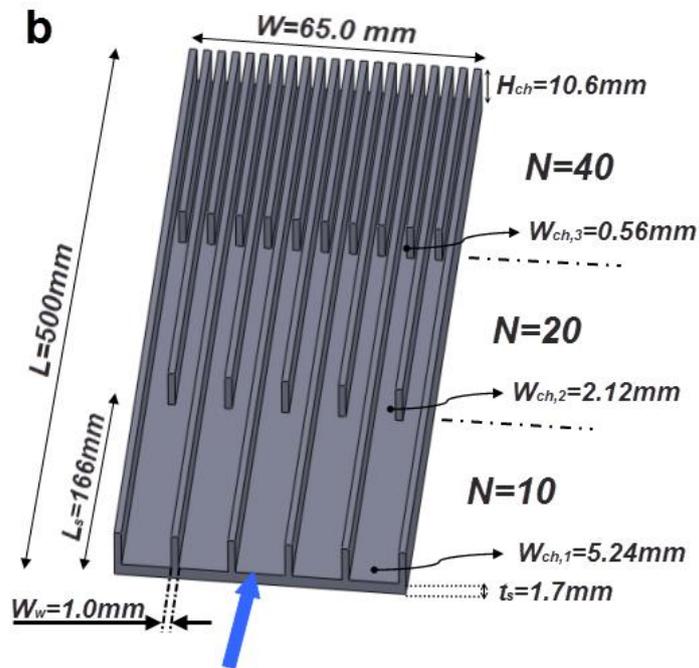
274 Two plate-fin cooling devices of different layout have been integrated into the system.
275 More specifically the devices comprise two matching, elongated plate-fin heat sinks
276 employing microchannels of either constant (FW configuration) (**Fig. 3a**) or stepwise-varying
277 width (VW configuration) along three consecutive sections (**Fig. 3b**), respectively. From a
278 manufacturing/structural point of view the devices fulfill the general criteria of compact and
279 lightweight layout, reliable and leak-proof operation, viz. development of low internal
280 pressure, ease of fabrication using conventional machining and thus low cost and convenient
281 layout for thermal bonding to the solar cell module. The thermal and hydrodynamic
282 performance of the heat sinks has been thoroughly investigated by the authors in [31-33],
283 while their geometrical parameters were determined using the optimization procedure
284 proposed in [30] by also taking into consideration the technical constraints posed by
285 conventional machining processes.

286 It has been verified through the previous studies [31-33] that the FW design (**Fig. 3a**)
287 obtains very low overall thermal-resistance values due to the large number of surfaces
288 (microchannels) available for heat transfer. The concept behind the design of the VW device
289 is to mitigate the pressure drop penalty, which is a major drawback of microchannel heat-
290 sinks, by employing two sections of low-fin density, as depicted in **Fig. 3b**. The complex
291 secondary flow pattern (longitudinal vortices) that emerges in the first two heat-sink sections
292 due to the effects of geometrical constrictions and buoyancy tends to disrupt the development
293 of the thermal boundary layer, hence increasing the thermal performance of the device despite
294 the subtraction of heat-transfer surfaces. In total, the VW device has been found to achieve a
295 superior hydrodynamic performance compared to the respective FW, with a minor decrease of
296 its thermal performance. Optimal devices in reference to each design have been manufactured
297 employing a multi-objective methodology, based on a genetic algorithm [30]. The total heat
298 sink length (500 mm) was dictated by the manufacturing procedure followed using a large-
299 scale milling machine. Likewise, the 65.0mm width was considered as the minimum ensuring

300 the rigidity of the device, since a very elongated and slender aluminum device would be prone
 301 to significant deformation during the soldering of the top heat sink cover.
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Fig. 3 Cooling devices employed in the CPVT system receiver: (a) FW configuration, (b) VW configuration.

312 **3. Evaluation of the concentrator optical quality**

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314 **3.1 Procedures followed for the experimental and numerical evaluation**

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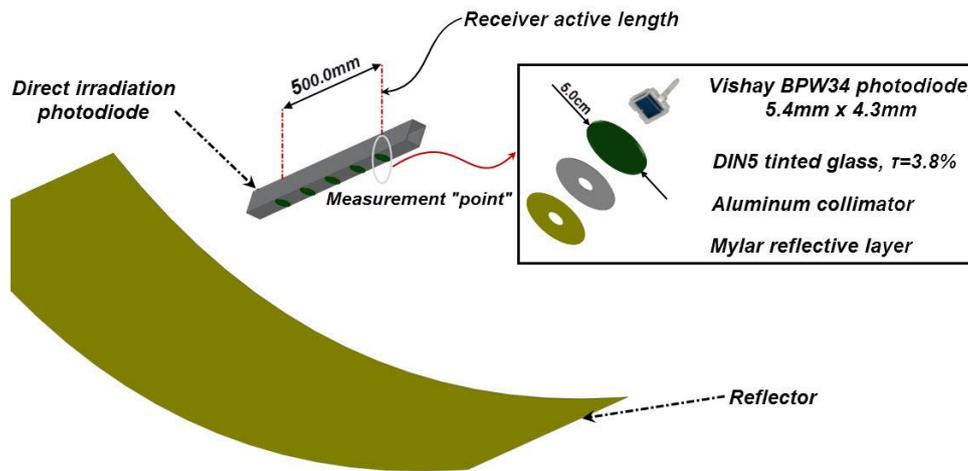
316 An important first step in the present investigation is the measurement of the transversal
317 and longitudinal irradiation flux distribution on the receiver. For this purpose, a measuring
318 device was developed comprising an array of photodiodes properly mounted on the bottom
319 surface of a rectangular hollow beam, as depicted in **Fig. 4**. The operation of the photodiode
320 is in principal similar to that of a solar cell, in the sense that the current produced is
321 proportional to the irradiation flux (e.g. in W/m^2) incident on the sensor aperture. The
322 averaged flux incident on the sensor aperture is converted to signal and hence there is no
323 influence of the irradiation incidence angle on its output. The so-called “cosine losses” [37],
324 an intrinsic feature of non-perpendicular irradiation, corresponding to the radiation
325 attenuation, as the incidence angle increases, has no effect on the accuracy of the flux
326 measurement, since all the rays incident on the sensor aperture contribute to the overall power
327 detected regardless of their angle of incidence. Besides, the suitability of photodiodes for
328 measuring the intensity of concentrated solar irradiation has been demonstrated in a number
329 of studies. Riffelmann et al. [38] and Lüpfer et al. [39] managed to measure the intercept
330 factor and the optical losses of the EURO TROUGH solar-thermal collector prototype using a
331 grid of photodiodes with diffuser filters mounted on a carriage that was positioned along the
332 receiver length with the use of a linear actuator. Pihl and Thapper [40] measured the
333 transversal irradiation distribution on the receiver of a low-concentrating CPVT system using
334 a device comprising a photodiode mounted on a rotating base. Chong and Yew [41] illustrated
335 the manufacturing procedure of a novel flux scanner employing photodiodes. An array of 25
336 photodiodes was mounted on a metallic frame that was able to move along two dimensions,
337 thus producing a grid of measuring points.

338 The sensors are unable to detect the spatial non-uniformity of light irradiance within their
339 active area; consequently a sensor of small size is required, especially when measuring the
340 transversal distribution, which exhibits high variation within a short length. Photodiodes with
341 rectangular aperture (5.4×4.3) mm^2 were used with tinted glasses as filters, in order to
342 prevent overheating under concentrated sunlight. The tinted glasses also served as light
343 attenuators to ensure that the photodiode response was well below the saturation region. Light
344 collimators were placed on the tinted glasses to cut out the diffuse part of the irradiation so
345 that the photodiode mainly detects the beam component of the light and also to prevent the
346 filters from overheating and rupture. A highly reflective Mylar tape was adhered on the
347 collimators in order to further reduce the heat absorbed by the filters. It was verified that the
348 filters could remain up to three minutes under concentrated sunlight prior to their rupture,
349 which is an adequate time interval to obtain meaningful results regarding the concentration. It
350 must be noted that two variations of the measuring device were developed for measuring the
351 longitudinal and transversal irradiation distributions, respectively. In regard to the
352 longitudinal-measurement configuration, the distance between consecutive sensors was equal
353 to 0.125 m and five photodiodes were placed to cover the entire receiver active length. Filters
354 of circular aperture with diameter of 5.0 cm were placed over the photodiodes.

355 In order to measure the transversal irradiation-flux profile, five photodiodes were housed
356 in holes drilled into an aluminum plate of dimensions 124 x 62 x 5 mm, which was
357 subsequently mounted at the bottom face of the beam. The intermediate distance between
358 sensors was equal to 15.0 mm, with the middle sensor being located exactly and the receiver
359 mid-width. The plate was able to slide along the beam length allowing the measurement of the
360 transversal profile at different longitudinal locations. A rectangular tinted glass was placed on

361 the plate to serve as filter, while the collimator had a narrow slit with width of 8 mm midway
 362 along its length.

363 The signal of the photodiodes was measured as current output, which is linearly
 364 proportional to the incident light power per unit area. The linear current response of the
 365 photodiode in proportion to the incident irradiation flux has been verified by the manufacturer
 366 and reported in the product datasheet [42]. The sensor linearity was further examined by
 367 retracting the light-attenuating filters from the grid of photodiodes and exposing them to
 368 direct sunlight. Excellent linearity of the sensors was verified with a correlation coefficient of
 369 0.995. Additional calibration studies were conducted in order to verify that the sensor signal
 370 closely followed possible fluctuations of the solar irradiation intensity. The signals of all the
 371 sensors employed showed a very good general agreement with the maximum discrepancy
 372 detected in both the transversal and longitudinal-measurement configurations being
 373 approximately equal to 8% [43]. This value (8%) was used as the experimental uncertainty in
 374 the values of the concentration ratio presented and should be primarily attributed to
 375 misaligned mounting onto the supporting hollow beam. The concentration ratio CR values
 376 were calculated by dividing the output of the photodiodes under concentrated sunlight by the
 377 output of a photodiode placed at the upper surface of the device and therefore measuring the
 378 direct, one-sun irradiation, as shown in Fig. 4. Irradiation flux values were produced by all the
 379 detectors, which can handle both concentrated and parallel light, and thus the CR values could
 380 be readily estimated.



381

382

383 **Fig. 4** Schematic of the device used for measuring the incident radiation on the system receiver.

384

385 In addition, a ray-tracing analysis was conducted in reference to the designed CPVT
 386 system, in order to predict the irradiation profile on the receiver. The analysis was performed
 387 with the commercial ray-tracing software TracePro [44], which utilizes the Monte Carlo
 388 method to predict the propagation of solar rays. A simplified geometrical model of the CPVT
 389 system was created, by omitting the supporting frame and base, and appropriate material
 390 properties were assigned to the system reflector and receiver, respectively. The solar
 391 irradiation was modeled as a circular sun source where all the radiation originates within a
 392 disc of radius 1.25m. The significantly larger sun-source area ($\approx 5\text{m}^2$) compared to the CPVT
 393 overall area (2m^2) ensured a uniform irradiation flux density on the reflector aperture for a
 394 large number of rays. A proper power value was assigned to each ray, in order the overall
 395 radiation flux emitted by the source to be equal to the beam radiation measured (in the order
 396 of 1.0 kW/m^2) for each case investigated. The influence of the concentrator deformation on

397 the irradiation distribution on the receiver surface was considered to be much more significant
 398 compared to the effects of sun-shape and circumsolar radiation distribution, which exhibit
 399 significant variations depending on the geographical latitude and the time of the year.

400 The system receiver was modeled as a perfect absorber ($\alpha=1.0$), as the focus is on the
 401 optical quality of the concentrator. In reference to the parabolic concentrator, two cases were
 402 considered, i.e. a perfectly specular mirror and an imperfect mirror that also induces light
 403 scattering (non-specular reflectance) due to surface and shape irregularities. In general, both
 404 specular and non-specular reflections occur simultaneously to some extent and the term
 405 “reflectance” is used for the ability of a material to reflect light in any manner [45]. Light
 406 scattering, i.e. widening of the solar band or beam spread has been taken into account in the
 407 ray-tracing simulations, in order to approximate the optical performance of the actual
 408 (imperfect) concentrator. The significance of light scattering induced by a surface was
 409 quantified in the simulations using the Bidirectional Scattering Distribution Function (BSDF),
 410 which is defined as the scatter radiance per unit incident irradiance:

$$411 \quad BSDF = \frac{G_{scat} / \Omega}{G \cos \theta} \quad (1)$$

412 where G_{scat} is the scattered irradiation within a solid angle Ω , and θ is the angle between the
 413 normal and a scattered ray. By imposing a value of the BSDF function, i.e. the “extent” of
 414 imperfections on the concentrator surface, a value of the specular reflectance is calculated by
 415 TracePro and the interaction of the incident rays with the imperfect concentrator is
 416 subsequently simulated. It becomes evident that the values of the concentrator specular
 417 reflectance explicitly corresponds to the extent of light scattering induced.

419 3.2 Irradiation-flux distribution on the receiver active surface

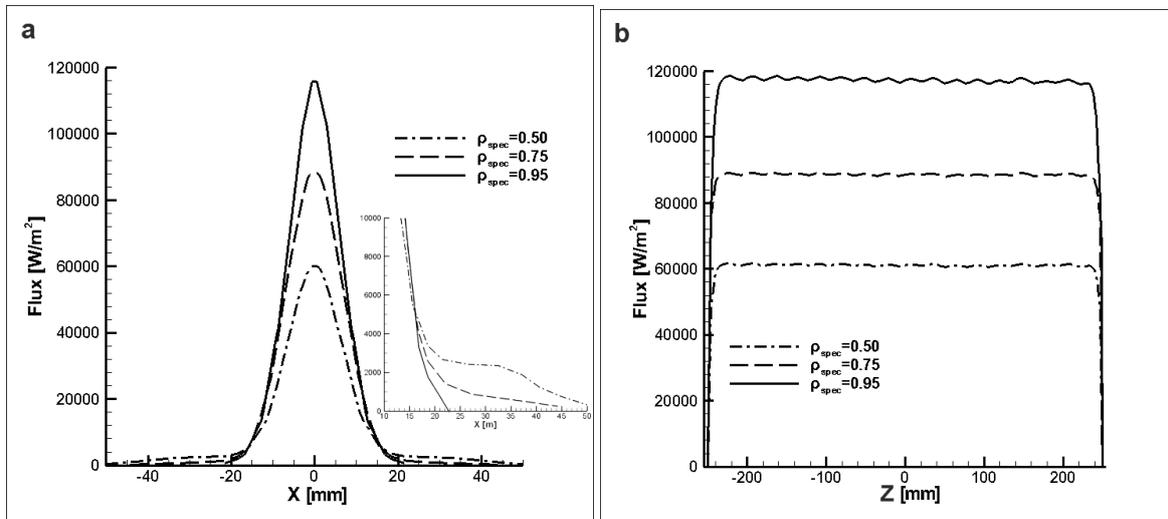
420
 421 An initial step in regard to the ray-tracing simulations was to conduct numerical tests to
 422 confirm that the results produced are independent of the number of rays simulated. For this
 423 reason, two benchmark cases were selected for completeness purposes, one for high
 424 ($\rho_{spec}=\rho=0.95$) and the other for low ($\rho_{spec}=0.50$, $\rho_{tot}=0.95$) optical quality of the reflector,
 425 respectively. The number of simulated rays was gradually increased from $0.5 \cdot 10^6$ to $6 \cdot 10^6$, in
 426 order to illustrate the effect on the values of maximum and average concentration ratio CR , i.e.
 427 of the maximum and average irradiation flux on the receiver, as well as on the width of the
 428 solar band. The overall emitted irradiation flux was maintained equal to 1.0 kW/m^2 in all
 429 cases. **Table 1** summarizes the variation of the quantities in question for the two cases
 430 considered and increasing number of rays. As can be seen from the values of **Table 1**, the
 431 only quantity that exhibits some discrepancy with the number of rays is the maximum
 432 concentration ratio. The values of **Table 1** corresponding to both cases, in essence, illustrate
 433 that the irradiation distribution on the receiver is virtually identical regardless of the number
 434 of rays assigned, for a number of rays higher or equal to $2 \cdot 10^6$. It was finally decided to
 435 produce the results using $2 \cdot 10^6$ rays, which were found adequate for obtaining high accuracy
 436 and smooth irradiation profiles, within a reasonable simulation time of approximately four
 437 minutes on an eight-core CPU.

438 **Table 1** Effect of the number of simulated rays on the produced irradiation profiles.

Rays($\cdot 10^6$)	$\rho_{spec}=0.95$			$\rho_{spec}=0.50$		
	CR_{max}	CR_{ave}	W_{band} [mm]	CR_{max}	CR_{ave}	W_{band} [mm]
0.5	113.4	22.5	62	62.2	14.2	123
1	112.6	22.5	62	61.8	14.3	123

2	112.5	22.5	62	61.7	14.3	123
4	112.4	22.5	62	61.7	14.3	123

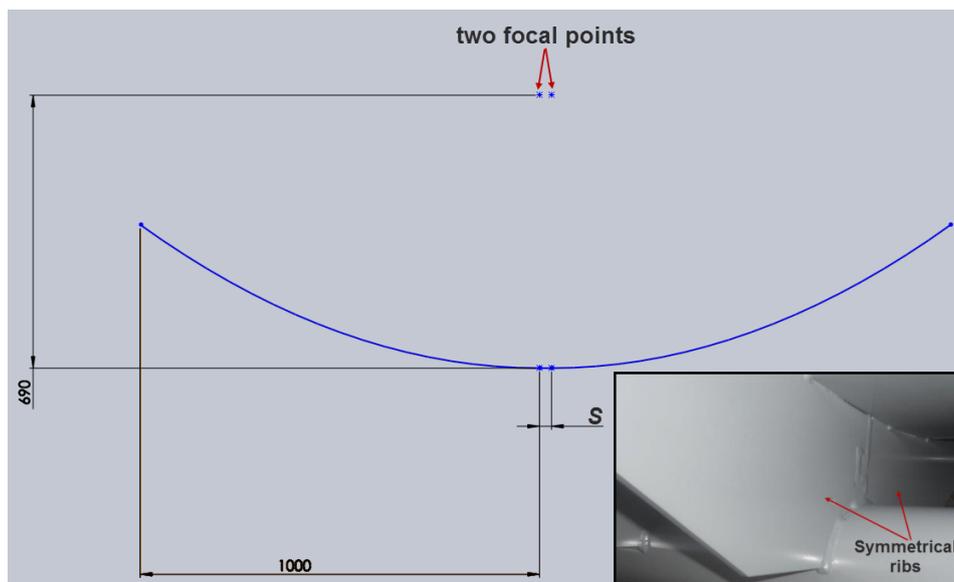
439 **Fig. 5** depicts the irradiation distribution on the receiver for concentrators of perfect
440 parabolic shape and different optical quality with three values (0.95, 0.75, 0.50) being
441 considered for the specular reflectance ρ_{spec} . It must be pointed out, that the material (overall)
442 reflectance is equal to 95% in all the cases examined, however the specular reflectance ρ_{spec} ,
443 reduces according to the BSDF value (see **Eq. 1**) imposed, in order to replicate the effect of
444 light scattering induced due to the reflector surface imperfections. The transversal profile
445 shown in **Fig. 5a** exhibits a normal (Gaussian) distribution for fully specular reflection
446 ($\rho_{spec}=0.95$). As the percentage of specular reflection decreases to 0.50, i.e. the concentrator
447 optical quality decreases and significant light scattering occurs, on the one hand, the peak
448 value of irradiation flux achieved decreases and, on the other hand, the form of the transversal
449 distribution deviates from the Gaussian distribution. The solar band becomes wider and the
450 profile exhibits plateaus of low concentration values at a distance spanning approximately
451 between 20.0mm and 50.0mm from the receiver mid-width, as depicted on the magnified view
452 of **Fig. 5a**. The form of the flux longitudinal profile, depicted in **Fig. 5b**, remains qualitatively
453 unaltered regardless of the value of specular reflectivity. However, as can be clearly seen the
454 concentration achieved at the focal line is approximately reduced by half as the specular
455 reflectivity reduces from 0.95 to 0.50, in accordance to the peak value of the transversal
456 profile. The receiver intercept factor was found to decrease in a linear manner with specular
457 reflectivity meaning that a significant portion of the incoming sunlight on the collector
458 aperture completely misses the receiver in the cases of non-specular reflectance and hence the
459 CPVT system performance degrades.
460



461
462 **Fig. 5** (a) Transversal and (b) longitudinal profiles of the irradiation distribution for concentrators of perfect
463 parabolic shape and different optical quality.
464

465
466 It was made clear from **Fig. 5a** that the transversal irradiation distribution exhibits a clearly
467 discernible peak at the receiver mid-width, regardless of the optical quality of the
468 concentrator. However, the irradiation measurements revealed a different transversal profile
469 with two regions of high irradiation intensity located on either side of the receiver centerline,
470 while the irradiation at the location where maximum irradiation was expected (receiver mid-
471 width), actually exhibited low concentration values. The fact that the profile exhibited
472 (relative) symmetry allowed the conclusion that the characteristic, dual-peak distribution did
473 not occur due to tracking error. Furthermore, since a two-axes tracking system was employed

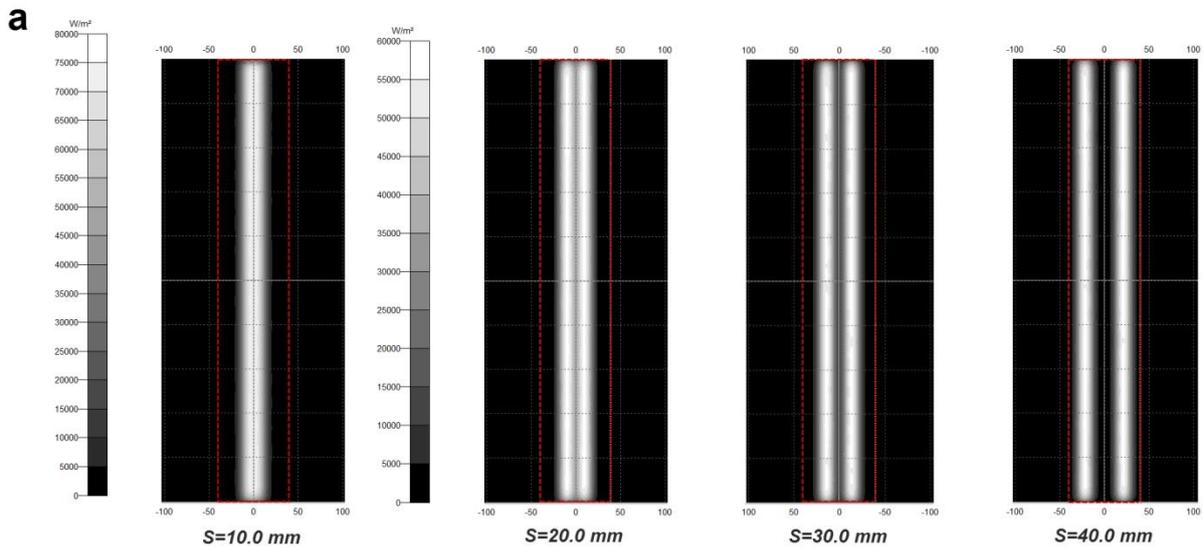
474 during the investigation, the solar irradiation was always perpendicular to the CPVT system
 475 aperture and thus there were no optical mechanisms (e.g. cosine or end losses) that could have
 476 possibly affected the form of the irradiation distribution on the receiver, which should have a
 477 typical Gaussian distribution. Therefore, the “dual-peak” profile must be attributed to the
 478 shape quality of the concentrator. An angular deviation of the parabola from its ideal shape,
 479 would in essence indicate that the actual focal length is different than the ideal one, e.g. see
 480 [45]. However, it has been demonstrated that off-focus operation tends to widen the focal
 481 band and produce a smoother irradiation profile. It was postulated that the shape of the
 482 parabola was distorted in the sense that the parabola apex was not a single point but instead a
 483 flat segment, denoted as S in **Fig. 6**, resulting in the existence of two focal points. This
 484 assumption can be supported by the procedure followed for the construction of the parabolic
 485 frame, as the metallic ribs that realize the parabolic shape were manufactured as two separate,
 486 symmetrical parts that were subsequently welded on the frame main shaft. The thickness of
 487 the welding joints, which are visible at the inset of **Fig. 6**, is small yet inevitably displaces the
 488 symmetrical ribs and distorts the shape of the parabola. Ray-tracing simulations were
 489 conducted to illustrate the effect of the distorted parabolic shape on the irradiation profile on
 490 the receiver. As was already mentioned, the displacement of the ribs must be small and thus
 491 values between 10.0 mm and 40.0 mm were considered as length for the segment S .
 492



493
 494
 495 **Fig. 6** Distorted form of the reflector parabola due to manufacturing imperfections.
 496

497 **Fig. 7a** presents the solar irradiation bands incident on the receiver for incremental
 498 geometric distortions of the parabolic concentrators, as produced by the simulations. It can be
 499 observed that two illuminated regions on either side of a dark region appear for values of the
 500 flat segment length S equal to or larger than 20mm. As the distortion length increases the two
 501 peaks shift away from the receiver center-line and the middle dark area becomes wider. In
 502 addition, the maximum irradiation intensity is significantly decreased for $S=20.0$ compared to
 503 that for $S=10.0$ mm. It is therefore made evident that small errors in the shape of the parabola
 504 can have a remarkable effect on the reflected radiation distribution. An actual photograph of
 505 the receiver under concentrated illumination is presented in **Fig. 7b** for comparison, where it
 506 can be clearly discerned that the center part of the cells remains un-illuminated, while two
 507 lines of high concentration are evident on either side of it. A thermal image of the receiver in
 508 operation, depicted in **Fig. 7c**, also demonstrates that the central part of the PV module

509 remains cool, while two linear regions, corresponding to the illuminated regions evident in
 510 **Fig. 7b**, of high temperature are evident on both sides of the central region. It can be therefore
 511 concluded that the actual irradiation distribution is accurately represented by the ray-tracing
 512 simulations.
 513



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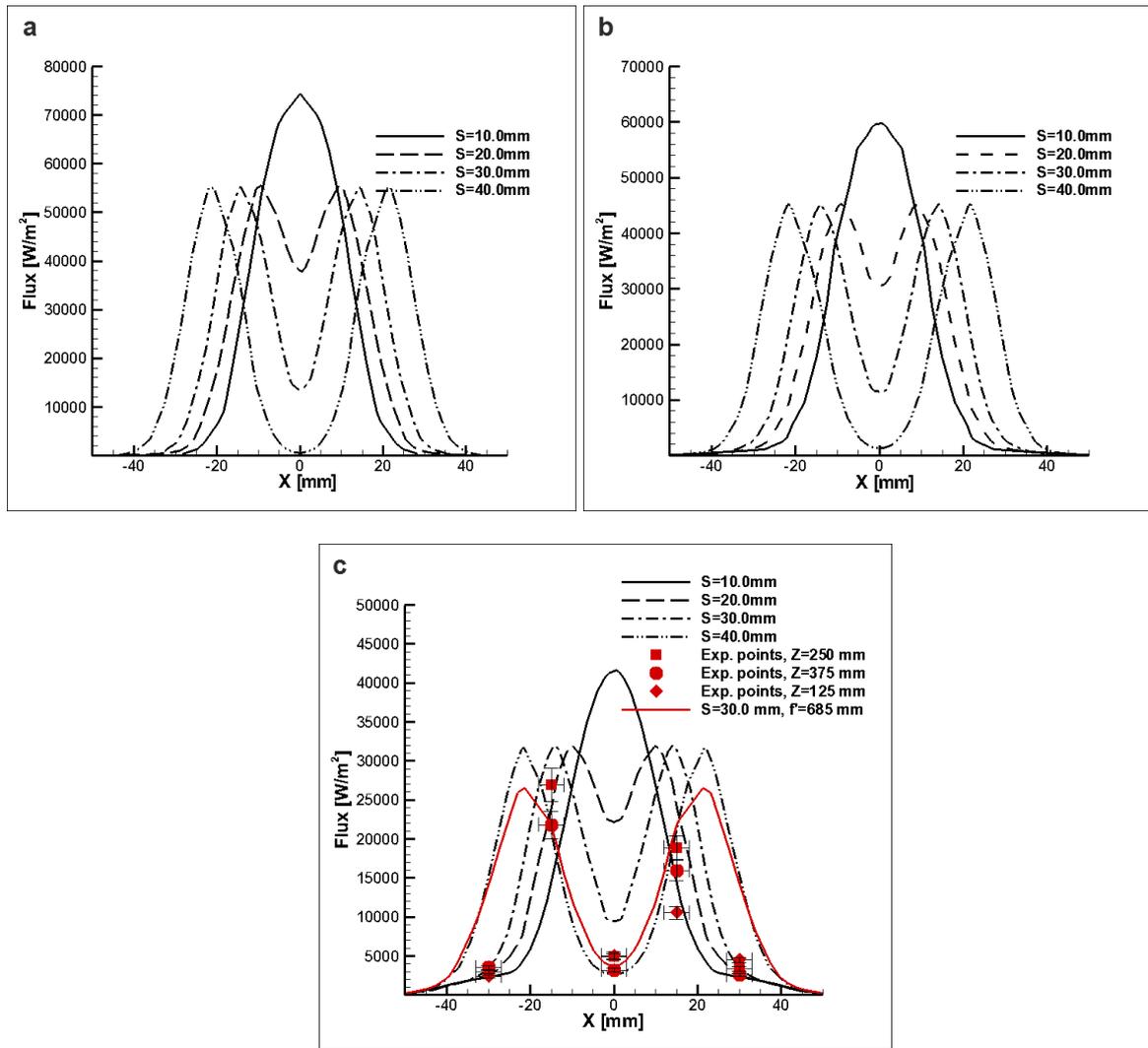
518 **Fig. 7** (a) Solar irradiation bands incident on the receiver for different lengths of the S segment ($\rho_{\text{spec}}=0.95$). (b)
 519 Actual illumination pattern on the receiver of the CPVT system. (c) Thermal image of the system receiver.
 520
 521

522 The “twin-peak” profiles are clearly evident in **Fig. 8** for $S \geq 20.0$ mm. Despite the profile
523 maintaining a single peak for $S=10.0$, the maximum concentration is reduced compared to a
524 perfect parabola. An additional observation, which applies for all two-peak cases regardless
525 of the value of specular reflectivity, is that the maximum flux value obtained remains constant
526 and unaffected by the length of the segment S . By comparing **Fig. 8** to **Fig. 6a**, it is made
527 clear that the maximum concentration achieved by a pseudo-parabolic shape having two focal
528 points is approximately half of that achieved by a geometrically perfect parabola. It must also
529 be mentioned that the profiles for each value of S exhibit a similar qualitative form for the
530 three values of specular reflectance considered.

531 Special attention must be given to **Fig. 8c**, where the concentration values measured across
532 the receiver width at five locations along the receiver active length ($Z=0.125, 0.250, 0.375$ m)
533 are also presented. It must be pointed out that the ray-tracing results presented correspond to
534 $\rho_{spec}=0.50$, indicating that the concentrator induces significant scattering of the reflected
535 radiation. As can be seen, the experimental points do lie between the predicted profiles for
536 $S=30.0$ mm and $S=40.0$ mm, but they clearly follow the same trend, i.e., with alternating
537 regions of low and high concentration. The asymmetry that can be discerned at the points with
538 $X=\pm 15.0$ mm could be due to displacement of the rib, as it could not be guaranteed that the
539 parabolic frame is perfectly symmetrical. Besides, the measurements at the three longitudinal
540 positions do not coincide, indicating that the parabolic frame is imperfect in a three-
541 dimensional sense.

542 The error in the receiver vertical displacement relative to the exact focal line can also have
543 a considerable effect on the flux distribution. The profile depicted with a red line in **Fig. 8c**
544 corresponds to a displacement error of 0.73% ($f'=685.0$ mm) in the receiver position and a
545 concentrator with distortion $S=30.0$ mm. It is evident that the profile is noticeably different
546 from the respective case with no displacement error. The profile is in fair agreement with the
547 experimental measurements and it is regarded as the best approximation of the flux profile on
548 the receiver. It is important to point out that the actual deformation of the concentrator is
549 anisotropic in a manner that cannot be predicted. An averaged effect of the surface
550 imperfections was imposed for the ray-tracing simulations through the BSDF values, along
551 with a characteristic deformation attributed to the lateral displacement S . However, the full
552 three-dimensional topology of the trough deformation cannot be captured by the simulations
553 nor the “point” solar-flux measurements. The distinct pattern of regions having low and high
554 illumination, clearly discernible in **Figs. 7b-c**, is clearly captured by the measurements, as
555 also by the simulations. Furthermore, the numerical and experimental evaluation allowed the
556 estimation of the maximum irradiation flux on the receiver surface, which was demonstrated
557 to be in the order of 25000-30000 W/m².

558



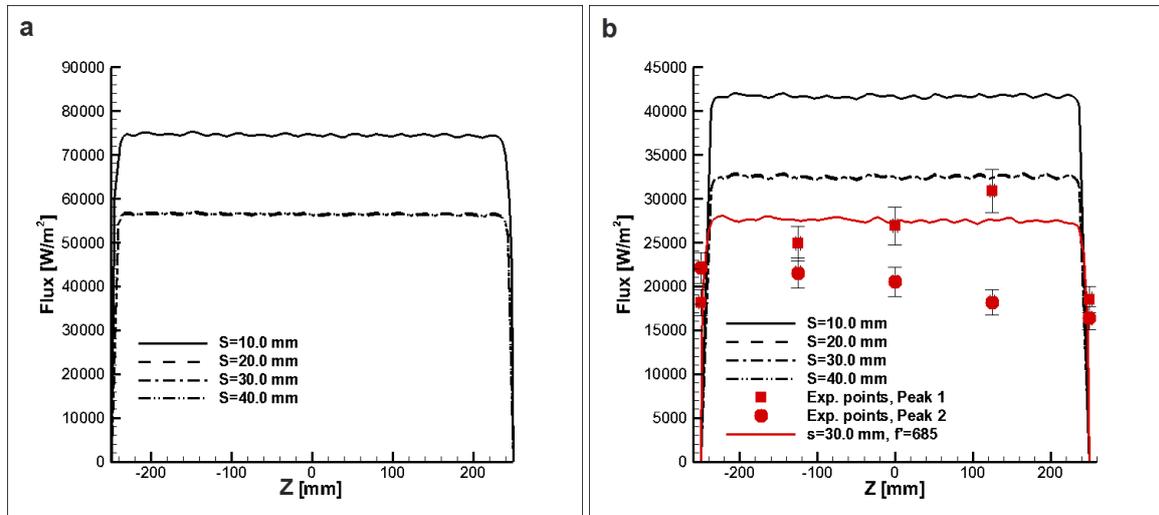
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Fig. 8 Transversal profiles of the irradiation distribution for “distorted” concentrators of different optical quality: (a) $\rho_{\text{spec}}=95\%$, (b) $\rho_{\text{spec}}=75\%$, (c) $\rho_{\text{spec}}=50\%$.

566 **Fig. 9** presents the longitudinal flux profiles for concentrators of different quality and
 567 distortion. The length of the segment S has no effect on the qualitative form of the
 568 longitudinal profiles but only affects the flux intensity. The profiles for $S \geq 20.0$ mm
 569 correspond to the transversal locations on the receiver, where peak concentration is obtained.
 570 The experimental values of the flux intensity measured along the receiver active length are
 571 also included in **Fig. 9b**. The length-wise distribution of the flux intensity clearly reveals that
 572 the parabolic frame is imperfect in a three-dimensional sense, as the concentration varies
 573 along the receiver length as well. The experimental values regarding the first peak are in good
 574 agreement with the ray-tracing prediction for $\rho_{\text{spec}}=0.50$, $S=30.0$ mm and $f=685$ mm, which,
 575 as was also mentioned for the transversal profile, appears to be the most reliable
 576 approximation of the actual distribution. On the other hand, the measured flux values
 577 corresponding to the second peak are lower than the predicted ones. This discrepancy, which
 578 is also evident in **Fig. 8c**, could be attributed to an increased slope error associated with only
 579 the one of the two symmetrical ribs that tends to widen the specific solar band. The slope
 580 error could be a result of imprecise manufacturing of the specific rib, but it is far more
 581 plausible to assume that the error occurs due to the uneven thickness of the punch-welding
 582 joints that bond the aluminum sheet realizing the parabola onto the ribs. As the welding joints
 583 are distributed along all the ribs and, in addition, there are several joints along the length of

584 each rib, they can be identified with great certainty as the main cause of the three-dimensional
 585 distortion of the parabolic surface, which consequently leads to a fully three-dimensional
 586 pattern of the scattered solar rays on the receiver surface.
 587



588
 589
 590 **Fig. 9** Longitudinal profiles of the irradiation distribution for “distorted” concentrators of different optical
 591 quality: (a) $\rho_{\text{spec}}=95\%$, (b) $\rho_{\text{spec}}=50\%$.

592
 593 **4. Experimental evaluation of the CPVT system overall performance**

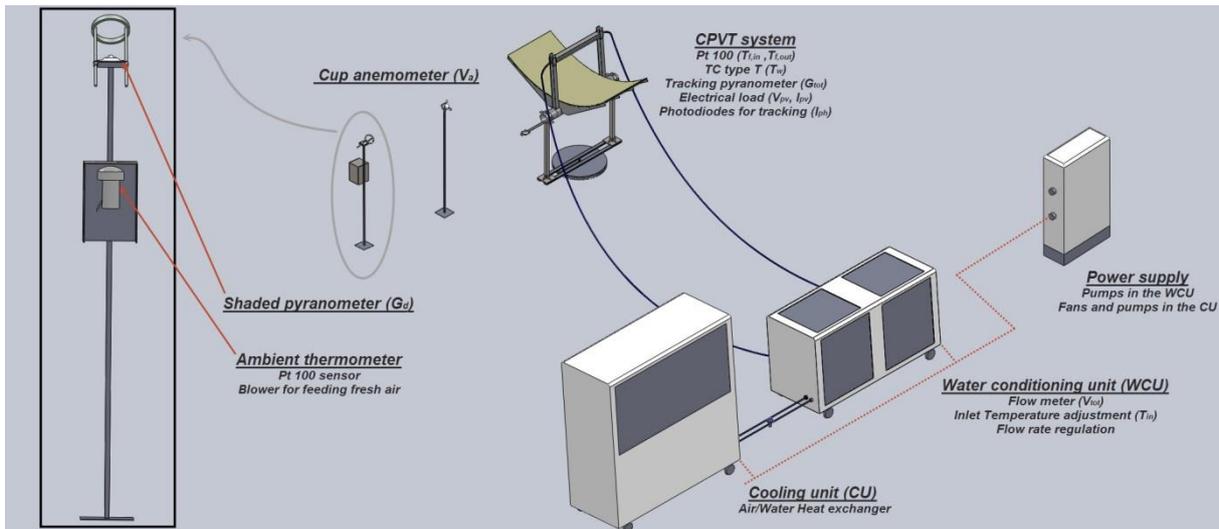
594
 595 **4.1 Description of the experimental setup**

596
 597 The electrical and thermal performance of the CPVT system was evaluated in an outdoor
 598 testing rig specially developed for this purpose (**Fig. 10**). The experimental setup comprised
 599 the electrical and hydraulic circuits, as well as the necessary instrumentation for the
 600 measurement of the quantities needed for the characterization of the system overall
 601 performance. It is important to point out that the prototype system does not include a storage
 602 tank and therefore there is no additional device intervening in the delivery of the thermal
 603 power produced to the thermal load. As illustrated by Fig. 10, the produced thermal power is
 604 eventually dissipated to the environment through the cooling unit (CU) incorporated in the
 605 test rig, which acts as the thermal load for the purposes of the performance evaluation.

606 Direct radiation G_b was calculated by subtracting the diffuse radiation G_d from the total
 607 radiation G_{tot} . For this purpose, two properly calibrated *Kipp & Zonen* (SMP 11)
 608 pyranometers of secondary-standard accuracy [46] were used. One instrument was mounted
 609 on the collector frame and tracked the movement of the sun in order to measure the total
 610 radiation perpendicularly incident on the collector, while the second was mounted on a static
 611 pillar beside the collector and was properly shaded using an appropriate ring manufactured by
 612 *Kipp & Zonen*, so as to detect only the diffuse part of the solar radiation. A properly shaded
 613 four-wire Pt100 temperature sensor manufactured by *Thies Klima* was used for the
 614 measurement of ambient temperature. A cup anemometer manufactured by *Thies Klima* was
 615 used for the measurement of the wind velocity. Water flow rate in the hydraulic circuit was
 616 measured with a ring piston flow meter manufactured by Aqua Metro. Two four-wire Pt100
 617 temperature sensors were used for the measurement of the fluid temperature at the inlet and
 618 the outlet of the collector. The temperature at the solid substrate of the PV modules and the
 619 heat sinks was measured with the use of type T (copper-constantan) thermocouples
 620 manufactured by *OMEGA*. A variable resistor (0-6Ω) capable of dissipating up to 200W to

621 the environment was used as electric load, in order to operate the solar-cell module at the
 622 point of maximum power production. The voltage across the module was directly measured
 623 by the data logger through additional copper wires soldered to the module leads, so as to
 624 avoid any voltage drop in the high current cables. The produced current was converted to
 625 voltage through a 1 mΩ shunt resistor and consequently measured by the data logger. The use
 626 of an analogue, variable-resistive load was deemed as a reliable and inexpensive solution to
 627 measure the I-V curves of the solar-cell modules. The power output of the PV modules for
 628 each value of the load, was directly measured by the data logger and thus it is not associated
 629 with any error. The operating point of maximum power output was also stored by the data
 630 logger. The signals of all instruments were carried to an Agilent 34901A data logger and the
 631 measured values were processed and stored to a computer using the Agilent VEE software
 632 [47]. Data were logged and stored in a file every five seconds.

633



634

635

636 **Fig. 10** Layout of the test rig developed for the evaluation of the system.

637

638 **4.2 Experimental uncertainty analysis and propagation of errors**

639

640 An uncertainty analysis based on propagation of errors, as described in [48], has been
 641 conducted in order to determine the resulting uncertainty of the calculated quantities due to
 642 the error associated with the direct measurement of primary quantities. Considering that a
 643 result R is calculated from a set of measured quantities x_i , $R = R(x_1, x_2, x_3, \dots, x_i)$; then the
 644 uncertainty in the calculated value is equal to:

645

$$646 \quad U_R = \left[\sum_{i=1}^N \left(\left(\frac{\partial R}{\partial x_i} \right) U_{x_i} \right)^2 \right]^{1/2} \quad (2)$$

647 where U_{x_i} is the uncertainty associated with the measurement of the values x_i . **Eq. (2)** is valid
 648 regardless of whether the measurement uncertainty is given in absolute or relative values. The
 649 uncertainty in the values of the measured quantities required for the system characterization
 650 are given for a confidence level equal to 95% and summarized in **Table 2**. In addition, it must
 651 be pointed out that the error in the electrical signals directly measured by the data logger was
 652 considered negligible, while the uncertainty in the measurements of the solar radiation, the
 653 volumetric flow rate and the fluid temperature presented in **Table 2** have been determined by

654 calibration procedures performed in the Solar and other Energy Systems Laboratory. The
 655 uncertainty associated with quantities deriving from the directly measured ones was
 656 calculated by making use of **Eq. (2)** and are presented in **Table 3**.

657
 658
 659

Table 2 Uncertainty in measured quantities.

Measured quantity	Uncertainty U
V_{air} [m/s]	1.90%
T_a [K]	0.054
G_{tot} [W/m ²]	1.41%
G_d [W/m ²]	1.41%
\dot{V}_{tot} [m ³ /s]	1.76%
T_f [K]	0.054 K
T_w [K]	0.5 K
V_{pv} [V]	-
I_{pv} [A]	-
W [m]	0.025%
L [m]	0.1%

660
 661

Table 3 Uncertainty in calculated quantities.

Calculated quantity	Uncertainty U
A_a [m ²]	0.10%
G_b [W/m ²]	1.99%
Q_{th} [W]	2.29%-2.90%-3.46%
P_{el} [W]	-
η_{th} [-]	3.52%
η_{el} [-]	2.05%
η_{tot} [-]	4.06%

662
 663

664 4.3 Environmental and operating conditions

665

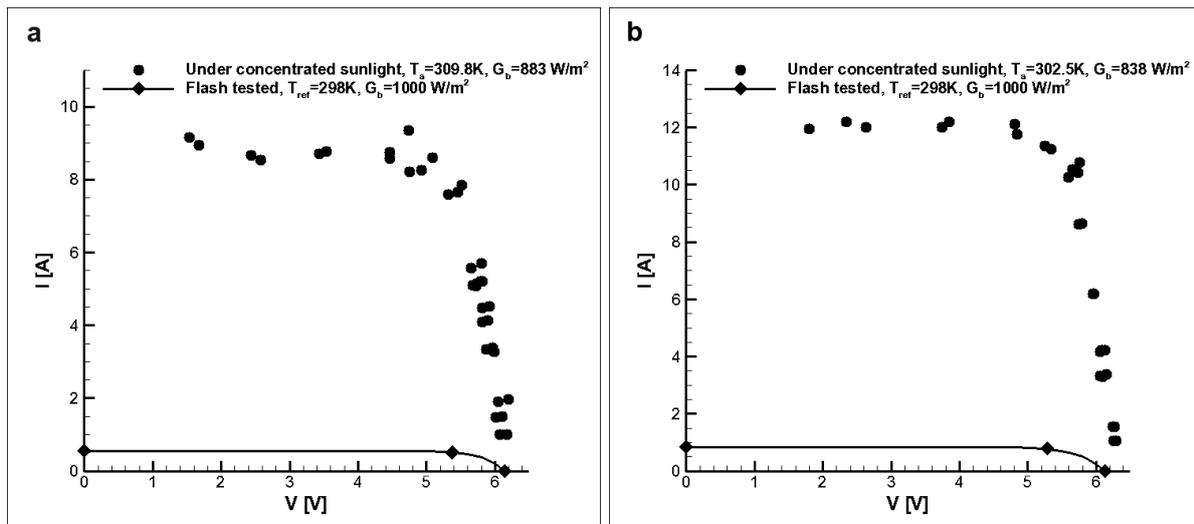
666 The performance of the integrated CPVT system was assessed for three variations of the
 667 system receiver comprising different PV module-heat sink combinations aiming at clearly
 668 illustrating the influence of the performance characteristics of receiver constituents on the
 669 overall efficiency and possibly designate the most attractive configuration. The efficiency
 670 measurements presented in the following paragraphs were performed in the summer and
 671 autumn period of 2014 at a latitude of 38°. The direct beam radiation, wind velocity and
 672 ambient temperature varied within the ranges 760-970 W/m², 0-2 m/s and 288-308K
 673 respectively, for all the testing sequences. Two-axes tracking of the solar irradiation was
 674 realized in all test cases, in order to avoid the effect of cosine and end losses on the
 675 performance of the CPVT system. Perpendicular irradiation was verified through the
 676 maximization of the output signal of a photodiode placed at the upper surface of the system
 677 receiver.

678

679 4.4 Characterization of the PV-modules electrical performance

680

681 An initial stage for the assessment of the modules electrical performance was to determine
682 the IV curves that characterize their operation under concentrated sunlight. For a specified
683 flow rate of the cooling fluid, the system was allowed to reach steady-state conditions and
684 then the value of the external load was gradually varied between its minimum and maximum
685 values (0-6 Ω), so as to cover the entire operating range of the modules. Measurements were
686 taken every 5 s and enough experimental points were obtained within two minutes, in order to
687 derive the I-V curve. Hence, the I-V curve for each module could be obtained for, in essence,
688 a constant irradiation value, constituting the measurement reliable. **Fig. 11** presents the
689 experimental points obtained for two PV modules assembled with narrow (**Fig. 11a**) and wide
690 (**Fig. 11b**) cells, respectively. The IV curves for one-sun irradiation as resulted from a flash-
691 tester measurement (at $T_{ref} = 25^{\circ}C$) are also included in the figures for comparison. It can be
692 discerned that the modules regardless of the cell design obtained an open circuit voltage V_{OC}
693 approximately equal to 6.2V. However, the module with the wide (60.0mm) cells produced a
694 short circuit current I_{SC} approximately equal to 12A, considerably higher compared to the
695 approximately 9A produced by the module comprising narrow (40.0mm) cells. It is essential
696 to point out that the solar-cell modules under concentrated irradiation has a power output in
697 the order of 55-75W, while the power output for typical solar irradiation is in the order of 3W.
698 The enhanced electrical output of the wide-cell module should be primarily attributed to its
699 larger active area, since the solar band has been significantly widened due to excessive light
700 scattering induced by the concentrator surface imperfections, as was demonstrated in the
701 previous paragraph.
702

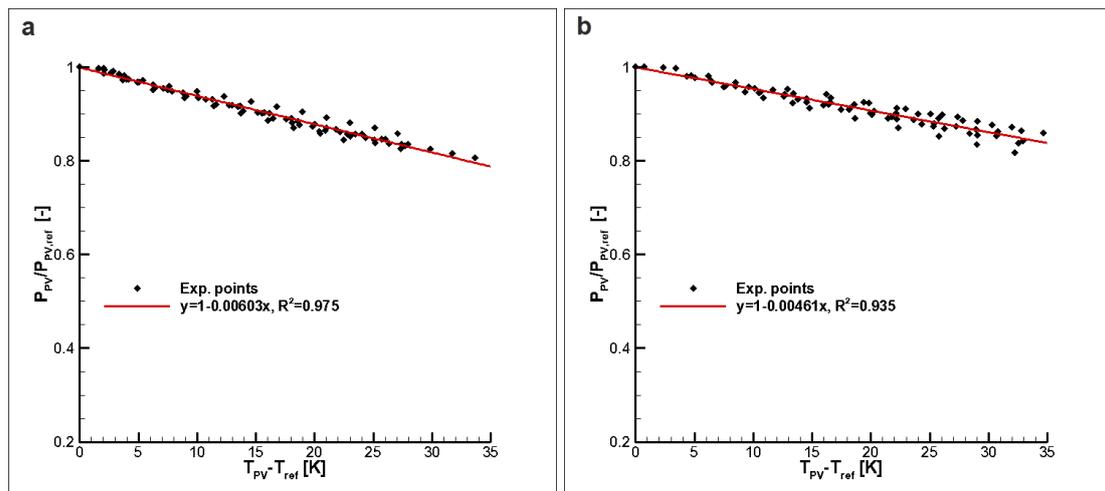


703
704
705 **Fig. 11** IV Curves for (a) the narrow-cell module and (b) the wide-cell module.
706

707 The solar-cell modules were operated under concentrated sunlight without the presence
708 of a heat sink, in order to evaluate the deterioration in their performance due to the elevated
709 temperature. The resistive load was appropriately fixed so that the modules operated close to
710 their maximum power point. The produced electrical power, the module temperature along
711 with the direct solar irradiation and the ambient temperature were recorded at intervals of 3s,
712 in order to keep the overall time period of each testing sequence as short as possible and thus
713 minimize any effect on the results of a possible fluctuation of the environmental conditions or
714 temporary loss of normal incidence. Two type-T thermocouples symmetrically attached to the
715 mid-width of the back substrate were used for the measurement of the module temperature.

716 **Fig. 12** shows the relative change in the module performance as a function of the
717 temperature difference to ambient. The results were taken on consecutive clear days under

718 slightly different environmental conditions and good repeatability of the measurements was
 719 achieved. As made evident by both **Figs. 12a and 12b**, the expected linear decrease in
 720 performance is verified [49]. However, the rate of decrease is steeper in the case of the
 721 “narrow” solar cells, which is a clear indication that the “wide” cells are better suited for
 722 operation at elevated temperature. The difference in the behavior of the two cell designs can
 723 be attributed to the series-resistance value that characterizes each design. According to the
 724 values provided by the manufacturer, the series-resistance value is higher for the narrow-cell
 725 module, equal to 0.70 Ω instead of 0.49 Ω for the wide-cell module, and by taking in mind
 726 that the series-resistance increases linearly with temperature [50], the power dissipation
 727 within the module and thus the performance deterioration is more pronounced for the narrow
 728 cells.
 729



730
 731 **Fig. 12** Effect of temperature on the solar-cell module performance: (a) narrow cells, (b) wide cells.
 732
 733

734 4.5 Thermal and electrical performance of the CPVT system

735
 736 At the present time, there is no official standard available for the performance
 737 characterization of CPVT systems [51]. Therefore, and regarding the system thermal
 738 performance in particular, the quasi steady-state method [52,53], which applies to
 739 concentrating solar thermal collectors, was employed. According to the method, the system
 740 efficiency is determined for a set of prescribed operating conditions, while requirements are
 741 also posed for the prevailing environmental conditions. The limits regarding the prevailing
 742 environmental conditions, as well as the constraints posed on the variation of the main
 743 physical quantities, in order for the experimental test to be considered valid are shown in
 744 **Table 4**.

745 The flow rate selected for the measurement of the system thermal efficiency should
 746 represent actual operating conditions, while the PV module should be operated at the
 747 maximum power point. The time interval required for obtaining an experimental point must
 748 be in the order of 3-5 minutes and thus the rotating base of the CPVT system allows the
 749 acquisition of a large number of experimental points in each testing sequence, as near-normal
 750 incidence can be achieved throughout the entire daylight period, reducing in this way the
 751 evaluation time period.
 752
 753

Table 4 Requirements of the quasi steady-state method.

Absolute constrictions	
V_{air}	$<4.5 \text{ m/s}$

G_b	$>630 \text{ W/m}^2$
$G_{b,\max}-G_{b,\min}$	$>200 \text{ W/m}^2$
θ	$\approx 0^\circ$
Constraintss in variance	
T_{in}	1% or 0.2°C
$T_{f,out}-T_{f,in}$	4% or 0.4°C
$\dot{m} C_p$	1%
G_b	4%
T_a	2°C

754 The maximum electrical output that can be extracted from the PV module is equal to
755 $P_{el}=V_{MPP}I_{MPP}$, where V_{MPP} and I_{MPP} are the voltage and current produced by the module when
756 operating at the maximum power point. During the experimental evaluation, operation under
757 maximum power output conditions was verified by adjusting the load resistance accordingly,
758 so as the product of the cell voltage times the produced current to be maximized. It must be
759 mentioned that the device employed is less accurate than a digital MPP tracker, yet much
760 more simple and inexpensive. Besides, the main objective of the present proof-of-concept
761 study is to characterize the CPVT system in terms of overall performance, which will not be
762 affected even if the PV module may not operate exactly at the point of maximum power
763 production, since the irradiation not directly converted to electricity will be instead exploited
764 as thermal power. The system electrical efficiency can be defined as:

$$765 \eta_{el} = \frac{V_{MPP}I_{MPP}}{A_a G_b} \quad (3)$$

767 where G_b is the direct irradiation and A_a is the reflector active aperture. Provided that the
768 system has reached steady-state operating conditions, the thermal efficiency can be calculated
769 as follows:

$$770 \eta_{th} = \frac{Q_{th}}{A_a G_b} = \frac{\dot{m} c_p (T_{f,out} - T_{f,in})}{A_a G_b} \quad (4)$$

773 where \dot{m} , $T_{f,in}$, $T_{f,out}$ are the specified coolant mass flow rate and temperature at the receiver
774 inlet and outlet, respectively. A linear model is commonly employed for the approximation of
775 the system thermal efficiency as follows [53]:

$$776 \eta_{th} = \eta_0 - U_0 \frac{\overline{T_f} - T_a}{G_b} \quad (5)$$

779 where η_0 is the optical efficiency, namely the efficiency achieved by the system for negligible
780 thermal losses to the environment $\overline{T_f}$ the mean coolant temperature in the receiver and U_0 is
781 the thermal-loss coefficient. The optical efficiency is correlated to the receiver intercept factor
782 and the properties of the reflector and the receiver materials as follows [37]:

$$783 \eta_0 = \rho \tau \alpha \gamma \quad (5)$$

786 where ρ is the total reflectance of the reflective surface, τ is the transmittance of the glass
787 cover, α the absorptance of the receiver active area and γ is the intercept factor of the
788 receiver. The system overall efficiency was calculated by the simple summation of the
789 respective thermal and electrical efficiencies, namely $\eta_{tot}=\eta_{th}+\eta_{el}$.

790 The system efficiency for the different receiver configurations considered is illustrated in a
791 comparative manner in **Figs. 13a-c** with the water volumetric flow rate being equal to
792 30mL/s. The direct irradiation values for all the experimental points are presented in **Fig. 13d**
793 for completeness purposes. In all the cases examined, the temperature rise within the receiver
794 was in the order of 3.5-4K, depending on the operating point, while the fluid inlet temperature
795 lied in the range 298-323K. An initial observation can be made that the system optical
796 efficiency, i.e. the system overall efficiency for negligible heat losses, is in the order of 50%,
797 which implies that half of the radiation incident on the system aperture is lost due to the
798 system optical quality. Based on the results of the ray-tracing simulations for the distorted
799 parabolic shape (see §3.2), the intercept factor of the receiver was estimated equal to 0.57
800 (**Fig. 14**) and thus the additional 7% of irradiation lost must be attributed to the transmittance-
801 absorptance product $\tau\alpha$ of the PV module.

802 It is interesting to notice that the optical efficiency is approximately 2% higher in the
803 systems employing PV modules with 60mm-wide cells (**Figs. 13a-b**). The enhanced optical
804 efficiency is justified considering that the cell material, which has an anti-reflective coating,
805 occupies a larger module area in the case of the wide cells, while a portion of that area is
806 substituted by reflective anodized aluminum in the narrow-cell modules. The comparison of
807 **Figs. 13a-b** also reveals that the receiver employing the worse performing wide-cell module
808 (**Fig.13b**) achieves higher thermal performance compared to the receiver corresponding to
809 **Fig. 13a** due to the additional power available to be extracted as heat. Hence, the
810 interdependent nature of the electrical and thermal efficiencies of a CPVT system becomes
811 evident. In any case, the system overall efficiency is dependent only on its quality
812 characteristics, such as optical efficiency, thermal losses and possible parasitic power.

813 The maximum electrical efficiency is in the order of 7.0% and is achieved by a wide-cell
814 module (**Fig. 13a**). On the other hand, the maximum efficiency achieved by the narrow-cell
815 modules is lower and approximately equal to 5.0% (**Fig. 13c**). The discrepancy in the
816 efficiency of the two module designs is primarily attributed to the extent of their active area,
817 as the width of the solar band is even larger than the 60mm-wide cells and thus the irradiation
818 spillage outside the cell active area becomes significant especially for the narrow, 40mm-wide
819 cells (see **Fig. 7b**). Besides, the significant irradiation non-uniformity is the reason for the low
820 efficiency of all the PV modules as, besides the significant irradiation spillage, the cells are
821 primarily illuminated in the regions close to the busbar, while the bulk material at cell mid-
822 width receives irradiation of much lower intensity (see **Fig. 8**). It has been demonstrated by
823 Coventry [15], that partial illumination of a solar-cell leads to significant decrease of its
824 efficiency and consequently a uniform irradiation profile across the cell width would be ideal,
825 in terms of performance. It is necessary to point out, and in reference to **Fig. 13b**, that the
826 efficiency of the PV module comprising wide cells is lower by 2% absolute than the
827 respective value for the module with identical geometrical parameters referring to **Fig. 13a**.
828 The decline in the performance of the former module occurred on grounds of improper
829 connection to the electrical load, as was identified after the testing completion and not on the
830 module manufacturing quality. However, the overall system efficiency could be reliably
831 evaluated, due to the interdependent nature of the system electrical and thermal output.
832 Hence, the experimental data obtained were reckoned as valuable for the characterization of
833 the overall system performance.

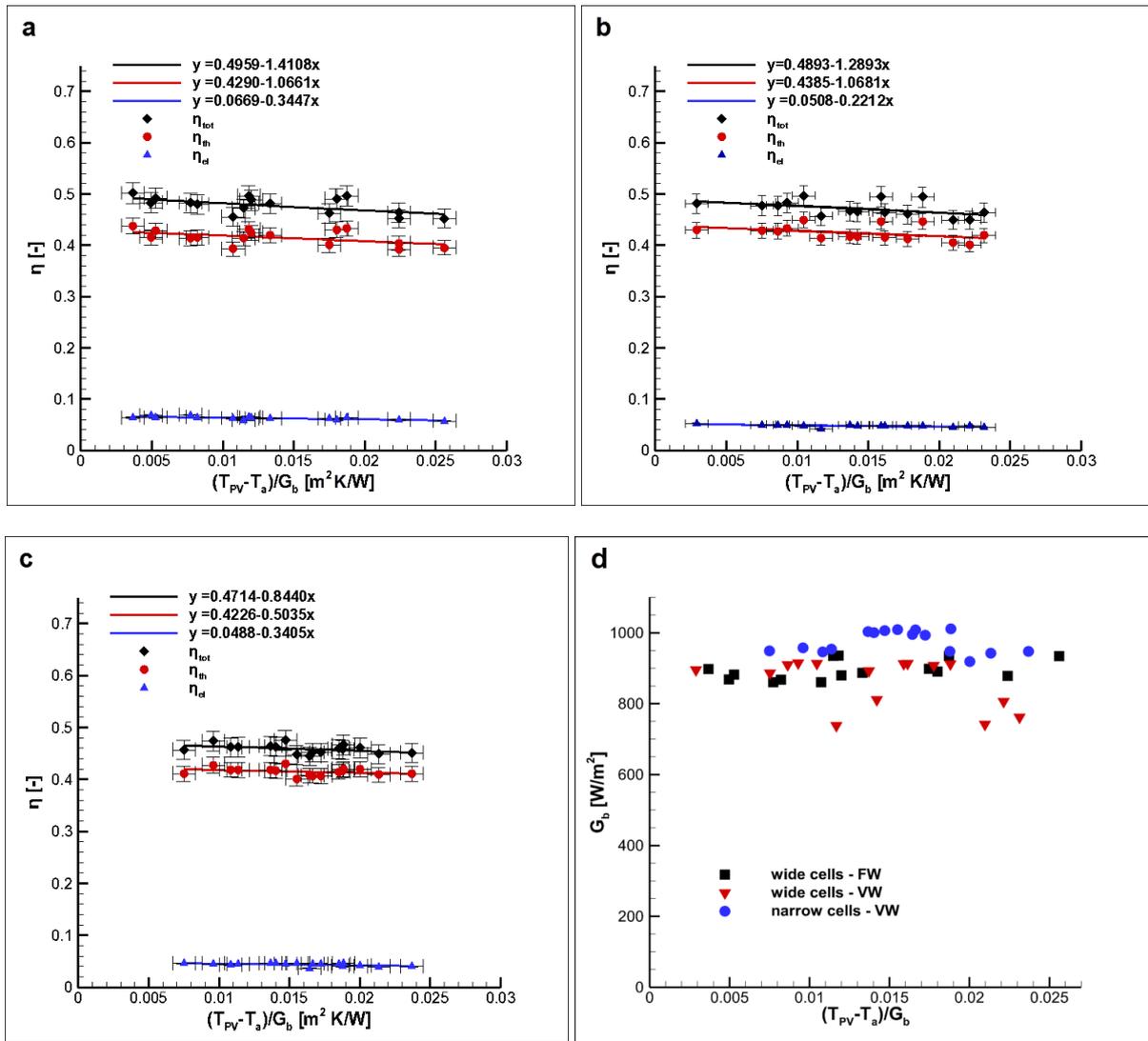
834 It is also made evident by **Fig. 13** that the system thermal efficiency exhibits a weak
835 dependence on the operating temperature, i.e. heat losses are relatively insignificant. This is

836 due to the cooling of the PV module, the compact heat-sink configurations and the use of
837 heavy insulation, which lead to minimal convection and radiation losses from the PV-module
838 front glass cover, as well as, to minimal conduction losses from the receiver back surfaces,
839 respectively. It must be noted that the receiver configuration employing the narrow-cell
840 module and the VW cooling device (**Fig. 13c**) was insulated using expanded polystyrene
841 ($k=0.033 \text{ W/mK}$), which seems to be a more appropriate material in comparison to Armaflex
842 that was used for the other configurations. This is made evident by the heat-loss coefficient of
843 the specific configuration ($U_0 \approx 0.5 \text{ W/m}^2\text{K}$), whose value is approximately half of the
844 respective ones obtained for the other configurations. A theoretical estimation of the receiver
845 thermal losses, which are highly dependent on the fluctuating environmental conditions,
846 performed in [43] revealed that they are in the order of experimental uncertainty.
847 Furthermore, the power consumption of the pump required to circulate the working fluid has
848 been measured to be in the order of 0.2 and 0.04W for the FW and VW heat-sink devices
849 respectively, due to the small overall system length [43]. Hence, the deduction that the
850 incident irradiation is approximately “split” to useful power output and optical losses is
851 verified.

852 A finding of significant importance that derives from the comparison of **Figs. 13a** and **13b-**
853 **c** is that the system achieves similar overall performance regardless of the employed cooling
854 system (FW or VW device). It is rational to expect that heat spreading is significant within the
855 receiver material layers with high thermal conductivity (aluminum substrates), as the
856 irradiation non-uniformity on the receiver surface and the non-uniform quality of the thermal
857 bonding between the module and the heat sink should create a fully three-dimensional
858 temperature field within each layer. Thus, it is plausible to conclude that heat losses are well
859 designated by the average heat-sink temperature. An experimental investigation that has been
860 conducted to determine the thermal performance of the cooling devices [43], which is not
861 presented here for brevity, verified that the values of the thermal resistance based on the
862 average wall temperature were approximately equal for the two devices, a fact that gives
863 grounds for the respective similar thermal performance of the CPVT system variations.
864 Therefore, the VW heat sink design appears to be a more attractive choice for incorporation in
865 large scale systems, whose efficiency will be significantly affected by parasitic pumping
866 power, as a much lower pressure drop penalty in comparison to the FW design is induced.
867 Regarding the VW design, it has been verified in [43] that the power required for pumping the
868 fluid through the heat sink is reduced by approximately 85% compared to the respective
869 required by the FW configuration. In addition, the VW configuration achieves a more uniform
870 cooling of the solar cells, which could also enhance the electrical production of large-scale
871 systems [31,32].

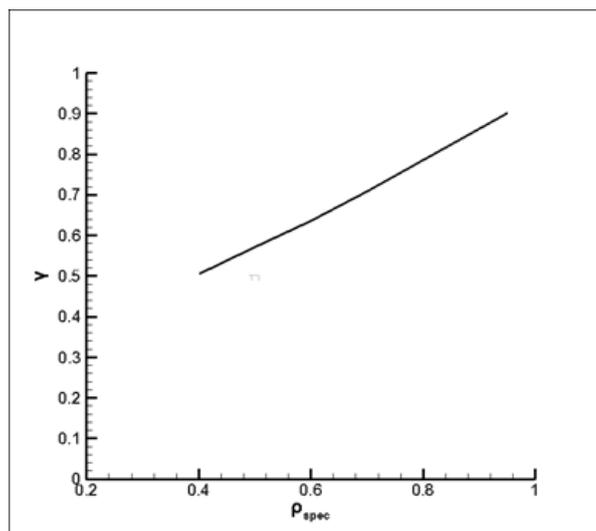
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Fig. 13 Thermal (η_{th}), electrical (η_{el}) and overall (η_{tot}) efficiency of the CPVT system for flow rate 30ml/s: (a) wide cells-FW heat sink, (b) wide cells-VW heat sink, (c) narrow cells-VW heat sink.



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Fig. 14 Receiver intercept factor vs. specular reflectance (total reflectance equal to 95%).

5. Basic cost constituents of the CPVT system

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Considering an active aperture area of 1.0 m^2 and an overall efficiency of 50% for the CPVT system, the cost per produced power, based on the actual prices of all the prototype components procured, was found to be approximately equal to 7.2 €/W . The respective cost for concentrating photovoltaic systems and concentrating solar applications, in general, is estimated to be in the range $3.0\text{-}7.5 \text{ €/W}$ [54,55]. In any case, the newly acquired know-how in reference to the design and manufacturing of the CPVT system allows for a great margin in cost reduction, especially if a more extended production is considered.

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The cost associated with the custom-made metallic parts, as reported by the industrial partners, can be reduced to 200 €/m^2 regarding the parabolic frame and to 380€ for an integrated heat sink-manifold configuration, considering a higher-volume production, e.g. of 100 items. Besides, *NAREC Ltd* estimated that for significant orders, e.g. in the range of 1000 cells, of a beforehand specified cell design, the cell cost can be reduced to as much as 15 €/cell . A PV module also comprises a low-iron glass front cover, conductive adhesive tape and an aluminum substrate. The values of low-iron glass can be as low as 35 €/m^2 for orders in the range of 50m^2 . The cost for the adhesive tape could be estimated equal to 7 €/m for large orders (200 m of tape), whereas the cost for the aluminum substrate can be considered negligible. By taking into account all the cost data mentioned above the overall cost for a PV module per m^2 of CPVT system active area, provided that out-sourcing for the assembly is not required, is estimated approximately equal to 155 € .

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The cost associated with the receiver insulation (Armaflex) is approximately 8 €/m^2 for orders of quantities greater than 10 m^2 . The costs for all the system constituents considering the reduced values for large-scale production are shown in **Table 5**. Consequently, an estimation for the relative overall cost of a CPVT system having an active area of 1.0m^2 yields a value approximately equal to 1.75 €/W . It must be noted that additional cost constituents, which can greatly vary depending on the system size, such as the cost of the actuator required for tracking or the inverter required in order to allow for the produced electric power to be delivered to the grid, have not been included in this analysis. In any case, it is evident that the cost per unit of produced power by the CPVT system, although it merely an initial rough estimation referring to a prototype device, is not prohibitive compared to other concentrated solar power applications.

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Table 5 Cost breakdown per m^2 of active area for “large-scale” production of the CPVT system.

Component	Cost
Parabolic frame	300 €
Reflector sheets	40 €
Heat sink	180 €
Nozzles	200 €
PV modules	155 €
Insulation	0.8 €

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6. Conclusions

The design, manufacturing and performance evaluation of an integrated, linear-focus CPVT system has been discussed in detail in the present study and the various technical issues associated with the realization of its sub-components have been thoroughly elucidated. A full-scale, prototype, parabolic-trough CPVT system has been successfully manufactured and experimentally investigated. The system optical analysis showed that the irradiation flux

925 distribution on the receiver active area was strongly affected by manufacturing limitations
926 associated with the concentrator shape, as it was revealed that the solar beam was
927 significantly scattered and excessive radiation spillage occurred reducing the receiver
928 intercept factor to a value of 0.57 and the system overall optical efficiency to approximately
929 50%. The experimentally-obtained irradiation distribution on the receiver active area
930 exhibited a dual peak profile, which was verified through ray-tracing simulations performed
931 considering a parabolic trough of slightly distorted shape at its apex. The deviation of the
932 irradiation flux profile from a normal distribution was found to have a negative effect on the
933 electrical performance of the system, as it was confirmed through actual observation and
934 thermal imaging that the central part of the solar cells was not properly illuminated, hindering
935 by this way the PV module performance. The prototype CPVT system was found to achieve
936 an overall efficiency of approximately 50% with thermal and electrical efficiencies of 43-44%
937 and 5-7%, respectively. It was furthermore established that the PV module comprising “wide”
938 (60.0mm) cells achieved a higher performance and was less sensitive to the increase of the
939 operating temperature compared to that consisting of “narrow” (40.0 mm) cells. The quality
940 of the novel heat-sink configurations developed by the authors was clearly demonstrated by
941 the evaluation of the system thermal performance, as their incorporation in the CPVT system
942 resulted in negligibly small thermal-losses coefficients ($U_0 \approx 0.5-1.0 \text{ W/m}^2\text{K}$). The VW device
943 was proved to be particularly well-suited for large scale systems, as it exhibits a similar
944 thermal performance to the respective FW layout, however with a significantly reduced
945 pumping-power requirement. Finally, from a techno-economical point of view, the overall
946 cost of a commercially-produced system has been estimated at 1.75 €/W, designating the
947 developed CPVT application a competitive option in comparison to other concentrating solar
948 technologies.

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