Outdoor and Indoor Testing to Increase the Efficiency and Durability of Flat Plate Solar Thermal Collectors

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Abstract This paper presents the test performed on the solar thermal flat plate collector and the effect of saline aerosol on the solar thermal conversion; an assembly of testing rigs developed in the R&D Centre Renewable Energy Systems and Recycling, in Transilvania University of Brasov, Romania is presented; the rigs allow outdoor testing of solar thermal flat plate collector in accelerated aging conditions: under stagnation and in saline aerosols. The corrosion/erosion effect of saline aerosols is investigated according to an original testing method. The results allow to formulate the preliminary prerequisites for developing novel standardized testing procedures.

Keywords Flat plate solar thermal collector · Outdoor testing · Durability · Accelerated aging test

1 Introduction

Large scale implementation of solar-thermal systems as part of the development of Nearly Zero Energy buildings requires efficient and durable flat plate collectors (STFPC). Standard testing is already formulated at international level for the main output properties, being linked to the conversion efficiency and durability, and represents a support in the developing novel, performance and cost-effective solutions. The International Association European Solar Thermal Industry Federation [1] reports on currently running testing procedures for the solar collectors: internal pressure, high-temperature resistance, exposure, external thermal shock,

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I. Visa (ed.), *Sustainable Energy in the Built Environment - Steps Towards nZEB*, Springer Proceedings in Energy, DOI 10.1007/978-3-319-09707-7_15

internal thermal shock, rain penetration, freeze resistance, mechanical load, impact resistance (optional), final inspection and thermal performance tests [1–3]. To perform all these tests, literature mentions the need for at least three collectors: one collector for assessing the thermal performance, the second for testing the durability, and the third is used for mechanical load and rain penetration tests.

There are two methods to evaluate the thermal performance of a solar collector: steady state and quasi dynamic test methods [4]. Each of these methods has advantages and disadvantages. In case of steady state method the advantage is its simplicity but the main disadvantage is related to a very large period of testing time in which the tests can be run due to the reduced number of days when all conditions are fulfilled (solar radiation, wind speed, etc.). In the case of the quasi dynamic testing method, the advantage is related to the reduced solar radiation intensity acceptable according to the standards, thus, for outdoor testing rigs, a triple number of days is available over one year, when the tests can be done.

Most of the performance standards are specifically designed for in-door or outdoor testing rigs and address the functional properties of un-used FPSTCs. On the other hand, the durability assessment requires accelerating aging tests, mimicking extreme operation conditions and registering the consequences on different parts of the collector and on the entire device. The focus is on two main causes that are responsible for the efficiency loss: (1) overheating during stagnation, responsible for the system's wearing, but mainly for the development of micro-cracks on the absorber plate and (2) corrosion/erosion of the absorber plate under saline aerosols that are likely when installing FPSTC on the seashore areas. Both causes lead to fast degradation and losses in the spectral selectivity, thus to a significant decrease in the conversion efficiency.

So far, the rain penetration standard addresses only the collectors' tidiness, and the corrosion/erosion measurements are standardized only for the absorber plate, ranking these according to their loss in the spectral selectivity, after the climatic chamber test. But, the tidiness (the polymeric sealing) can significantly be affected by the combination of heat and saline aerosols (common for many sea shore locations where solar thermal systems are installed), allowing the penetration of the latest and the reaction on the absorber plate during the working period, thus under solar irradiation (including UV and heat). This combination, having a significant variability in the content/ratio of the aggressive factors during the diurnal and seasonal cycles, needs to be initially tested in outdoor conditions and, after outlining the most important parameters, it can be transferred in in-door standardized procedures.

Thus specific aging tests are required, to investigate the FPSTC durability under these conditions and to validate the viability of the proposed solutions aiming at mitigating the effects of overheating, saline corrosion and their combination.

The paper presents an assembly of testing rigs developed in the R&D Centre Renewable Energy Systems and Recycling, in the Transilvania University of Brasov, Romania, supporting the quality assessment of FPSTC, under standardized and non-standardized procedures. Further on, the paper discusses the effect of saline aerosols on the solar-thermal conversion and, based on the outdoor testing results, preliminary prerequisites for developing novel standardized testing procedures are outlined.

2 FPSTC Testing Infrastructure

In order to evaluate the thermal performance of FPSTC, standard test EN 12975 describes in EN 12975-1:2006 the general requirements for solar thermal collectors and the first part and in second part are describing the testing methods [2]. To perform these tasks, certification stands can be either in-door or outdoor [5, 6].

As for the durability tests in saline environment for FPSTC, currently there is no standard in the word. In R&D Centre Renewable Energy Systems and Recycling (RES-REC), from Transilvania University of Brasov, Romania, has installed outdoor and in-door testing rigs for assessing the solar thermal performance of FPSTC and an out-door test rig for corrosion/erosion tests. The outdoor testing rigs are implemented on the rooftop of the laboratory building of the RES-REC Center, in the R&D Institute of the Transilvania University of Brasov. The location is at 45°66′ latitude, 25°55′ longitude, at 600 m above the sea level in a mountain region with an average amount of solar energy of 1,200 kWh/m^2/year, with large variations between the winter months (lower than 45 kWh/m^2/month during winter) and the summer months (over 150 kWh/m^2/month during summer).

For various tests related to FPSTC and their components, the relevant input data are measured on the testing rig (as required by the testing procedure). Additionally, the ambient parameters (solar radiation, wind speed and direction, temperature and humidity) are measured by the weather station Delta T installed near the outdoor testing rigs.

The out-door test rig presented in Fig. 1 was designed considering the specific objectives of the standard outdoor testing procedures. The testing rig also supports the research on overheating mitigation by using complex algorithms [7], thus it can be tracked by a bi-axial mechanical tracking system.

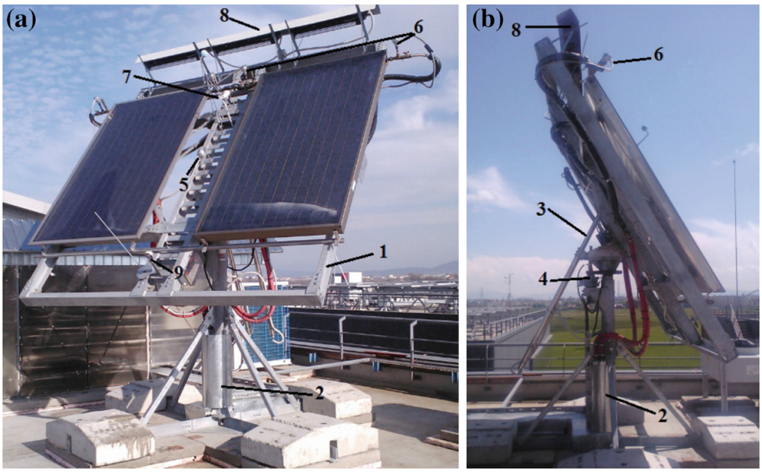

Fig. 1 Outdoor test rig for thermal performance. **a** Front view. **b** Left view

It consists of:

1. Solar-thermal platform frame (3 × 3 m^2) where two solar collectors with identical or different dimensions can be mounted;
2. Platform pillar; where the solar collector is mounted.

3 and 4. Bi-axial tracking system allowing the diurnal motion with an angular stroke of ±110° (gear based mechanism), while the elevation is insured by a linear actuator, (angular stroke of 10°–90°);

5. Pyranometer (class A) for global solar radiation measurement, installed in the solar collector plane;
6. PT100 sensors for inlet and outlet fluid temperatures;
7. Pyranometer with shadow ball (class A) for diffuse solar radiation measurement;
8. Ventilation units (maxim air speed 4 m/s);
9. Anemometer for wind speed measurement.

The regular tracking, for evaluating the collector's performance, follows the concept of theoretical maximum gain of available solar radiation. It is reached through a program that calculates the position of the sun in the sky depending on the day number and local time. Following data are subject of acquisition: global solar radiation; diffuse solar radiation, fluid inlet and outlet temperatures, mass flow, wind speed, elevation and diurnal angles.

Indoor FPSTC testing always brings complementary information on the FPSTC and allows ranking the collectors according to their functional performance. The indoor test rig, Fig. 2, consists of the following components:

1. Sun simulator; the intensity of solar radiation is of max. 1,000 W/m^2; the irradiation source is a mix of Vis- and UV bulbs, well mimicking the part of interest of the solar spectrum when analysing the conversion processes. The simulator allows therefore also PV testing;
2. Solar collector frame (1 × 2 m^2);
3. Pyranometer (class A), for global solar radiation measurement;
4. PT 100 sensors for inlet and outlet fluid temperature measurements;
5. Ventilation unit for wind simulation (wind speed 2 m/s);
6. Anemometer for wind measurement; temperature sensor (environment);
7. Sensor for mass flow measurement;
8. One axis tracking system, with linear actuator that allows an angular stroke of 0°–90°.

Following the need identified for extending durability tests on solar-thermal collectors by considering saline aerosols, a novel out-door test rig for corrosion/ erosion tests was designed and developed, Fig. 3:

1. STFPC frame, tilted at 45°;
2. Nozzles for spraying the saline aerosol; 25 nozzles are equidistantly installed on a pipe, allowing a homogeneous coverage of the collector's surface;
3. Plastic trough to collect the saline water at the bottom of the collector;

Fig. 2 Indoor test rig

Fig. 3 Out-door test rig for corrosion/erosion test

4. Storage tank (30 L) for the saline solution;
5. Recirculation pump (T.I.P. GPK46/42) with controllable flow;
6. Flow-meter (FIP FSIV032T, accuracy ±1.875 %).

The temperature and the humidity inside the collector are registered using a TPI597 device (Wales, ±0.5 % accuracy).

3 Results and Discussions

Complementary information is received from outdoor and indoor testing:

- Outdoor testing allows the acquisition of specific data that are close to the real output of the FPSTC, in the testing location; by extension it may be suppose a similar behaviour in geographic areas with a climatic profile close to the testing one. Outdoor testing also gives valuable information on the efficiency variation with the solar radiation profile (allowing the development of tracking algorithms for increasing the amount of solar input on the FPSTC surface) and gives an idea about the correlation solar radiation—duration—overheating, allowing the design of the algorithms aiming at mitigating the overheating effects.
- Indoor testing, under controlled radiation and wind speed allows differentiating among FPSTC and gives an accurate view on the tracking effect, since on the solar simulator there is only direct radiation.

If in the case of the outdoor rig information related to the method of testing, the place where the equipment is installed, the method to present the recorded data are clear, for indoor tests, the analysis of the existing standards allows the conclusion that the information on the testing procedure could be improved. The main improvement that could be done is to include an exactly specification of the devices used to measure solar radiation simulated. The measurement devices of the solar radiation are usually mentioned as pyranometer class A. Still comparative investigations, below described, suggest the need for a better description of the pyranometer.

3.1 Indoor Test

Indoor test of solar collectors involved to use a sun simulator. According to standard EN 12975:2-2006, light used to simulate the solar radiation must be in the range of 700 W/m^2, but can vary between 300 and 1,000 W/m^2. The spectral distribution of the simulated solar radiation shall be approximately to that of solar spectrum at optical air mass 1, 5 [2].

On the sun simulator described in Fig. 2, measurements of the input radiation were done using a pyranometer class A (Delta Ohm, LP PYRAN 03AC) and a lux-meter (MAVOLUX, 5032C/B). The results, expressing the global radiation should be equivalent. The correlations between the values recorded by the two devices are shown in Fig. 4.

As the results show, there is a good correlation at high irradiation but the values of the simulated solar radiation, between 200 and 400 W/m^2, there are certain differences between the recorded values from the pyranometer and the lux-meter.

Further on, a comparison between the measured values recorded by the pyranometer and the lux-meter when only the VIS lamps are switch on, is shown in

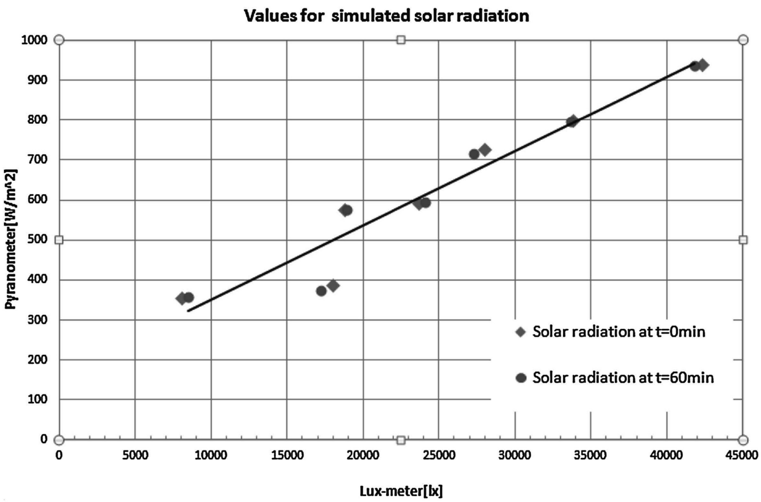

Fig. 4 Equivalent values of the simulated solar radiation (UV+VIS) as recorded by the pyranometer class A and by the lux-meter

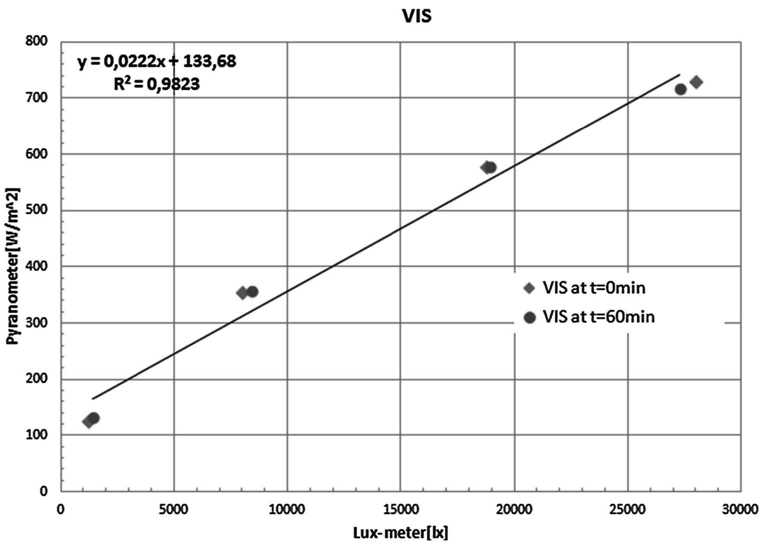

Fig. 5 Simulated solar radiation with VIS lamps

Fig. 5. The overlapping is good, leading to the conclusion that the differences registered in Fig. 4 are mainly connected to the measurement values in the UV spectral range. By applying linear regression on the measured values, the regression coefficient R is 0.9823, showing that, although an equivalency exists between the two types of measurements, these are not fully inter-changeable in Vis.

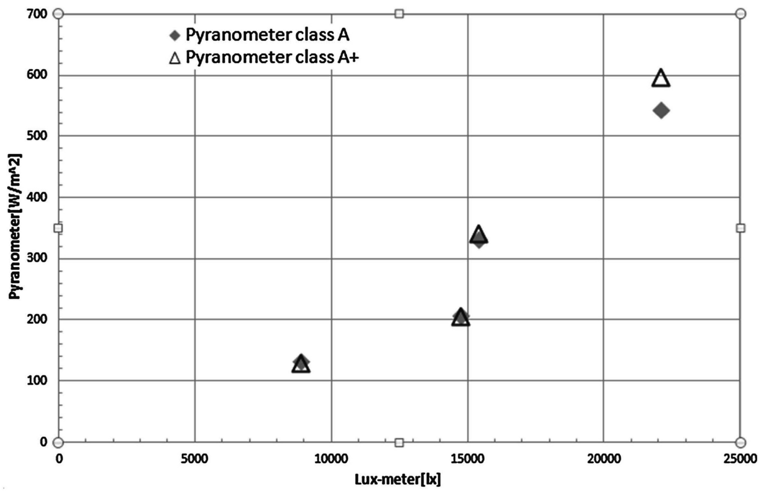

Fig. 6 Comparison between measure solar radiation with pyranometer class A or A+

In order to further investigate the pyranometer measurements similar measurements were performed using a pyranometer class A + (LSI LASTEM, BSR 153). By comparing the measured values using the two pyranometers (class A and class A+), Fig. 6, differences are outlined between the recorded values, considering as reference the data recorded by the lux-meter. The largest difference 54 W/m^2 occurs at high intensities of the solar radiation.

These results outline the need for specifying the type and accuracy of the device used for measuring the simulated solar radiation, for a correct estimation of the conversion efficiency.

Obviously, these conclusions can be extended also to outdoor measurements.

3.2 Outdoor Test for Saline Aerosol

Many applications of the residential solar thermal systems are in seashore areas where the climatic profile is mild and the number of sunny days is high. Because of this, there is an increased interest on the durability tests in saline environment applied to the solar thermal collectors (and to their components), [8, 9]. Several tests are developed for the casing and for the absorber plate, similar to the regular corrosion test of metals in the fog chamber (e.g. ASTMB117 and ISO 9227), but for the entire solar thermal collector there is no durability standard in saline environment (yet).

In an attempt to formulate a new quality criteria (durability in saline environment), a testing rig and a testing procedure were developed. Testing was conducted on the flat plate solar collector having air in the pipes and no circulation. This setup was chosen considering the different specific heats of air (1.005 kJ/kg K) and water (4.180 kJ/kg K) and the very large density differences (1,000 kg/m^3 for water and 1.12…1.29 kg/m^3 for air); using air allows thus sensing small variations in the temperature inside the pipes, under the outdoor irradiation conditions.

The tests covered 60 days, in three periods: in July–August 2013 (20 days) and in March–May 2014 (20 days from March 24 and 20 days from May 7); the first period is usually characterized by sunny days with high outdoor temperatures during the day; the second time interval is typical for a transient season (early to late spring) with significant and sudden variations in the solar radiation and with average outdoor temperatures (thus the risk of overheating is very low). Thus, the main functional situations were covered, corresponding to the periods when the collector is expected to well perform. From September to February, the FPSTC was left at rest outdoor.

Preliminary data on the July–August time interval were already reported [10], and allowed to identify two possible functions that could characterize the decay of the FPSTC, involving the FPSTC output temperature and the outdoor temperature: their difference and their ratio. Further on, to extend the database and to validate the conclusions already presented, the tests run during 2014 followed the same procedure; the recorded values were: the inlet and outlet air temperature inside the solar collector registered at 9, 12 and 15 o'clock, and the outdoor conditions at these moments (outdoor temperature, wind speed, humidity, and solar radiation). The comparative charts of the outlet temperatures obtained in the three periods is presented in Fig. 7.

The main challenge is to identify the most relevant experimental conditions and the optimal correlations between selected input and output data.

The solar radiation is not a fully useable data for a temperate climate as high intensity can be registered at very low outdoor temperatures (e.g. during sunny, frosty winter days), thus for the solar-thermal conversion, this is not the best parameter to be directly linked to the conversion efficiency and its decay. As the most important input data in efficiency calculations is the outdoor temperature, this was also hereby used.

In terms of output, the temperature at the FPSTC outlet (the outlet temperature) was considered as the suitable indicator of the solar-thermal conversion (as generally used in solar-thermal calculations).

A first correlation was attempted between the outlet FPSTC temperature and the ambient temperature. As expected, a similar trend was registered, for all three periods (in 2013, 2014) thus the correlation was not conclusive in either of the investigated moments: at 9:00, at 12:00 and at 15:00. Additionally, the data collected at 9:00 proved to be highly irrelevant as result of the low radiation profile. Therefore, in further correlations these data were no longer used.

Following the conclusions presented in [10], two functions were further investigated: the difference between the outlet and the ambient temperature ($T_{out} - T_{amb}$) and the ratio between these two: T_{out}/T_{amb}.

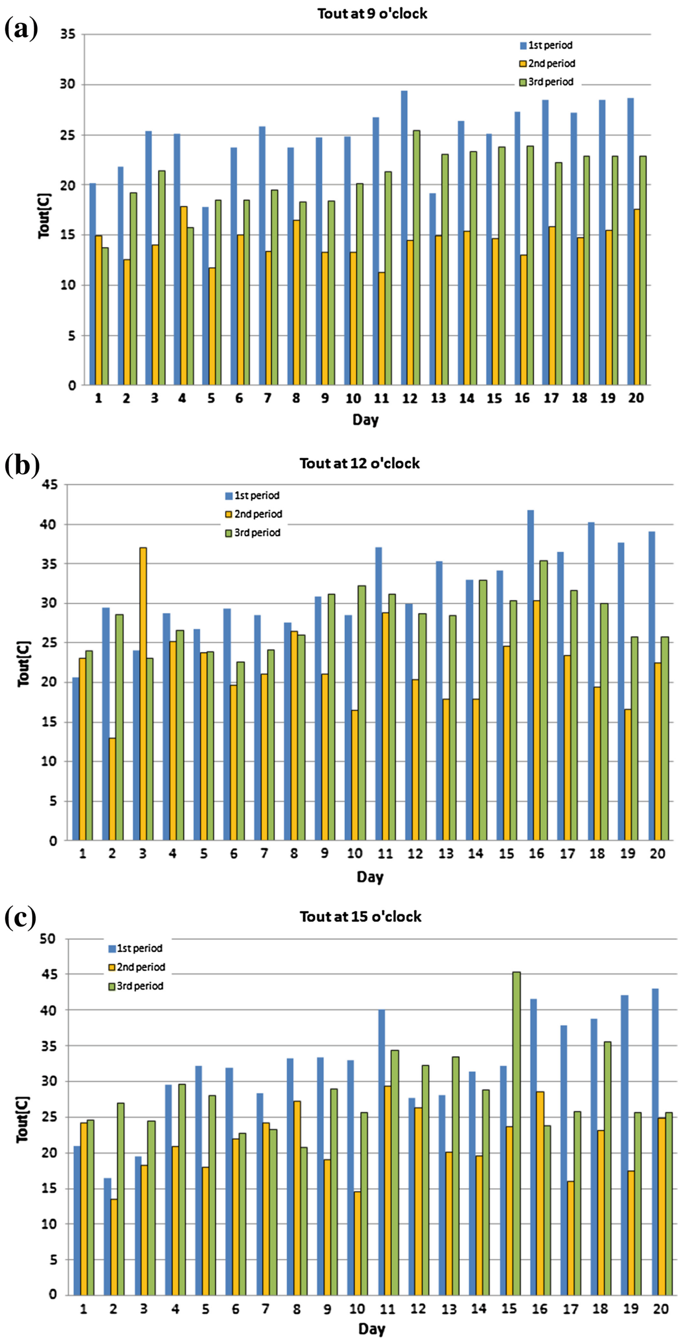

Fig. 7 Difference of outlet temperature for **a** 9 o'clock; **b** 12 o'clock and **c** 15 o'clock

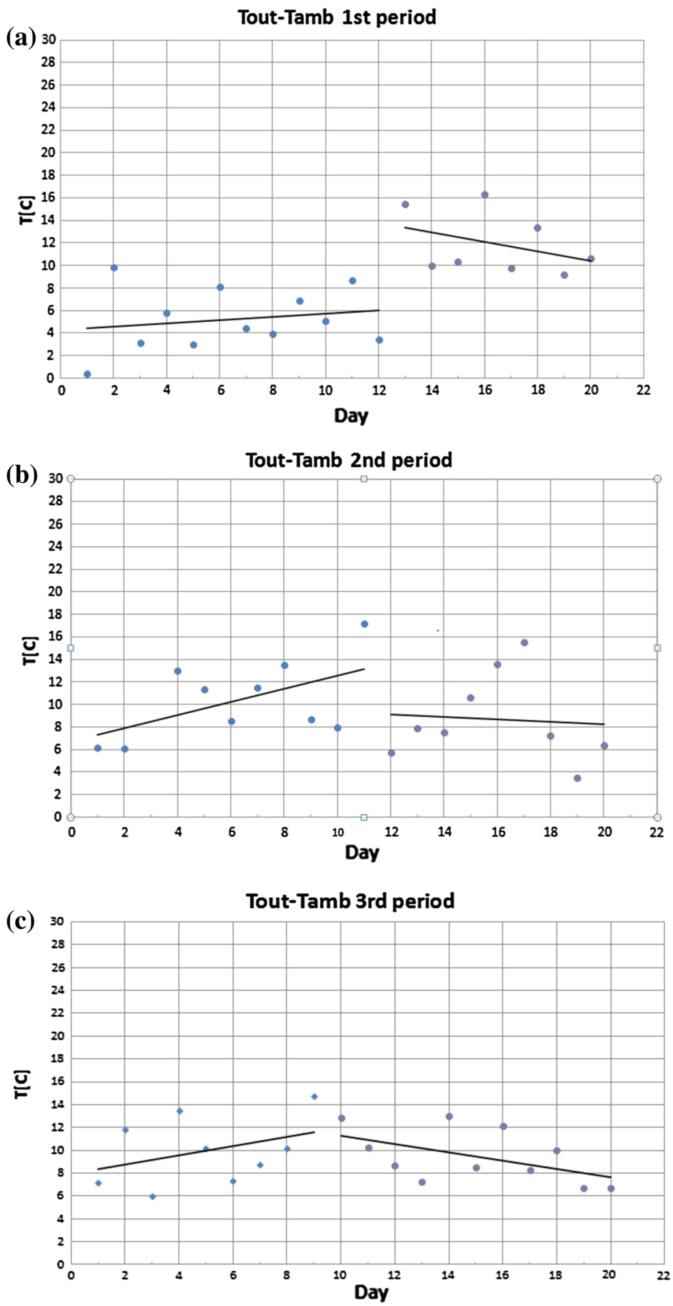

Fig. 8 Difference between the outlet and outdoor temperature at 12:00 during: **a** 1st period, **b** 2nd period and **c** 3rd period

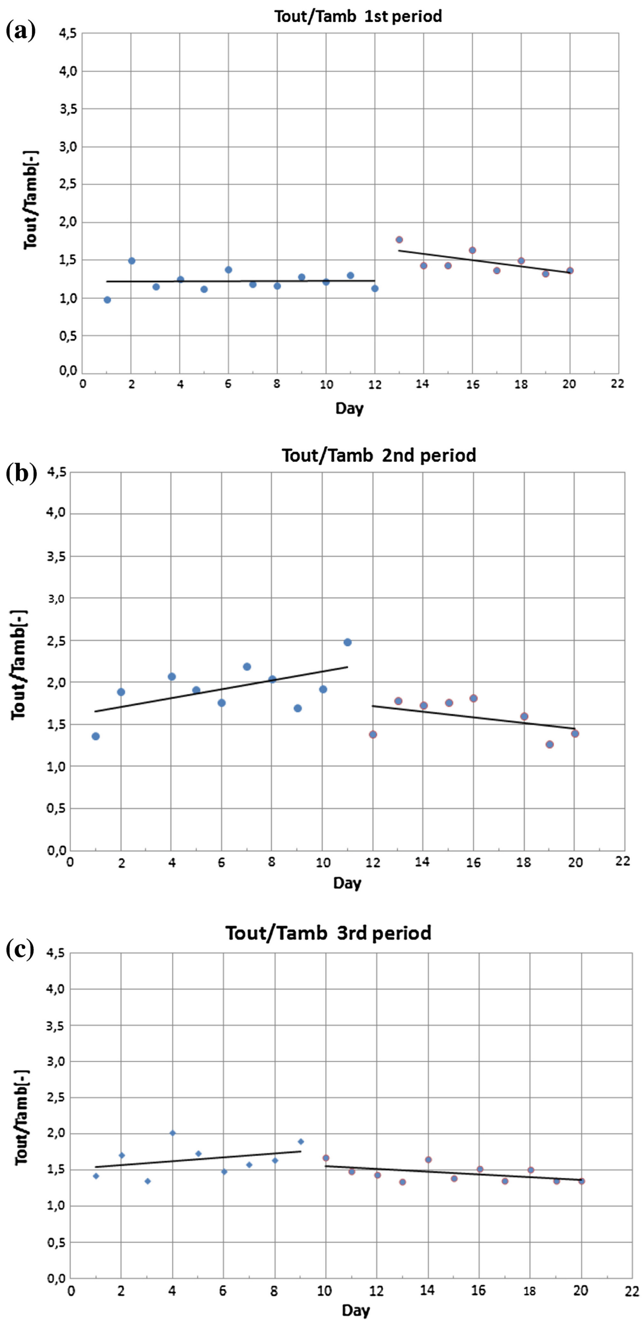

Fig. 9 Ratio between the outlet and outdoor temperature at 12:00 during: **a** 1st period, **b** 2nd period and **c** 3rd period

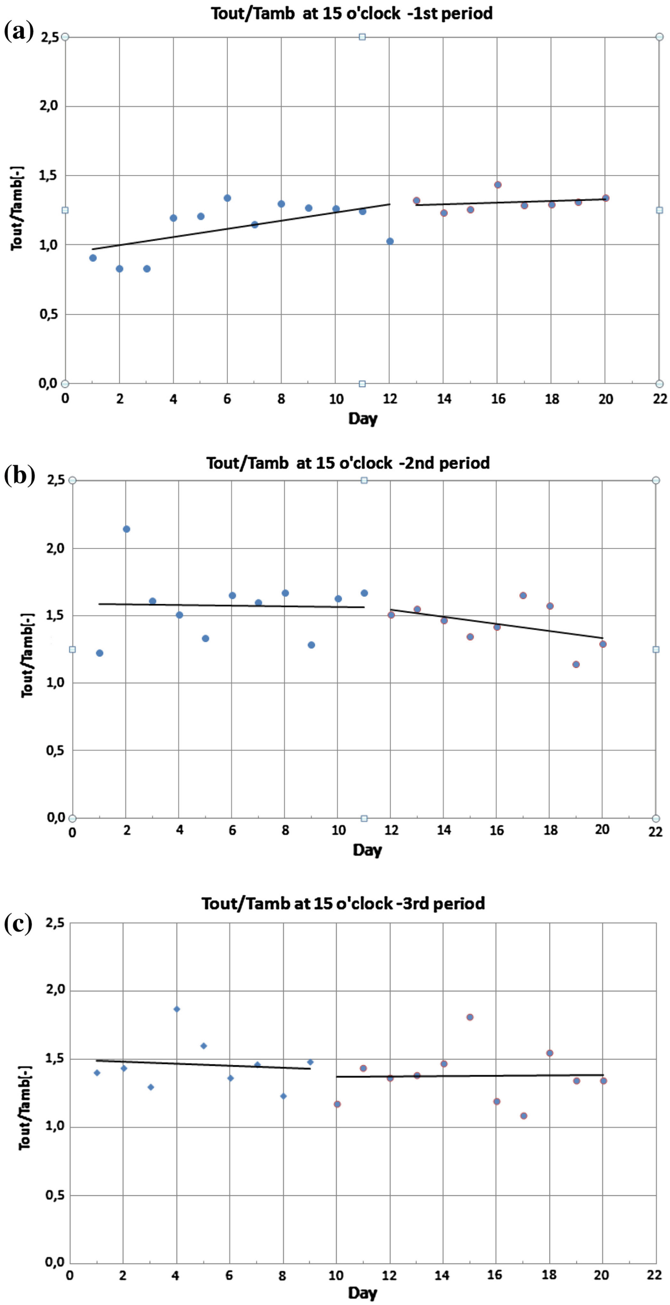

Fig. 10 Ratio between the outlet and outdoor temperature at 15:00 during: **a** 1st period, **b** 2nd period and **c** 3rd period

To give evidence on the best outdoor conditions able to outline the changes in the conversion efficiency (due to aging), these functions were calculated both for the data collected at 12:00 and for those registered at 15:00.

The graph variations over the three periods of 20 days represented based on the data collected at 12 o'clock are given in Fig. 8 and ($T_{out} - T_{amb}$) in Fig. 9 (T_{out}/T_{amb}). The same correlation functions ($T_{out} - T_{amb}$ and T_{out}/T_{amb}) were analysed also for the data collected at 15:00 but the slope changes are less evident thus the degree of uncertainty is higher. The ratio T_{out}/T_{amb} for the three investigated periods is presented in Fig. 10.

This recommends 12:00 (noon) as best testing period, outlining that the decay effect is more sensitive at higher ambient temperatures, thus it has the strongest influence when the output is at its best. This result outlines again the need for such tests as part of the re-design of the FPSTC components, particularly of the sealing which is mostly sensitive to the combination of heat and saline aerosols.

By analyzing the diagrams following observation can be obtained:

1. The outlet temperature has a decreasing trend for similar conditions of solar radiation and ambient temperature, as Fig. 7;
2. The saline aerosol test led to changes in the solar thermal flat plate collector behavior (abrupt change in the function variation); during the first testing period, changes in solar collector behavior appeared of the 12th day, in the second period changes occurred after 11 days, and during the third period changes were starting in the 9th days.
3. By comparing the set of measurements it can be concluded that the most sensitive to the changes in the solar collector behavior is the parameter given by the difference between outdoor temperature and the outlet temperature.
4. As Fig. 8 shows, this difference is decreasing from one testing period to another, showing the irreversible destruction of the absorber plate.

4 Conclusions

In assessing the efficiency (thus quality) of solar thermal flat plate collectors thermal performance and durability tests are required. Complementary indoor and outdoor tests can give a quite accurate evaluation of the new (un-used) FPSTC by following standardized procedures run on specific rigs. To get a common ground all over the world for the testing results, the paper shows that for indoor testing rigs additional info should be included in the testing methodology, especially related to the device that measures the input simulated solar radiation.

For the durability tests, saline aerosol/rain penetration tests were run outlining the influence of three sets of 20 days testing on the FPSTC performance. The results show that the tests are more relevant if run at higher outdoor temperatures (at noon). The most sensitive function in evaluating the decay due to accelerate aging was found to be the difference between the outdoor and outlet temperature.

Acknowledgments We hereby acknowledge the structural founds project PRO-DD (POS-CCE, O.2.2.1., ID 123, SMIS 2637, ctr. No 11/2009) for providing the infrastructure used in this work and the project PNII Cooperation Project, EST in URBA no. 28/2012 financially supported by the Romanian National Research Council.

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