Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 82 (2015) 744 – 751

Energy Procedia

ATI 2015 - 70th Conference of the ATI Engineering Association

Experimental Tests of Solar Collectors Prototypes Systems

Marco Ricci[a], Enrico Bocci*[e], Emanuele Michelangeli[b], Andrea Micangeli[c], Mauro Villarini[d], Vincenzo Naso[c]

[a]*Department of Astronautical, Electrical and Energy Engineering, DIAEE, Sapienza University of Rome, Italy*
[a]*Energy and Environment Department, Marconi University, Italy*
[c]*Interuniversity Center for Research on Sustainable Development, CIRPS, Rome, Italy*
[d]*Department of Agriculture, Forest, Nature and Energy, DAFNE, Tuscia University of Viterbo, Italy*
[e]*Department of Mechanical and Aerospace Engineering, DIMA, Sapienza University of Rome, Italy*

Abstract

Solar thermal collectors represent one of the most widely used technologies for heat production from renewable energy sources. To increase efficiency and to not increase too much cost different type of solar collectors, and in particular of evacuated tube collectors have been realized. In order to compare performance, tests at different conditions and in different configurations have to be performed. The aim of this paper is to establish the performance of a new prototype via an experimental evaluation of the performance in different conditions and configurations of three collectors. The prototype is particular owing to his new head configuration that permits an innovative parallel configuration way. Therefore, parallel and series configurations have been analyzed applying the UNI-EN 12975, in a steady-state regime. The efficiencies of the two configurations have been tested for different flow rates and different inflow water temperatures. The experimental results show that, with the same input flow rate to the single collector, the parallel configuration has higher performance than the series one, reaching 15% higher level of efficiency. Thus, it seems that these prototypes in optimized configuration can lead to a systems improvement, thereby increasing the overall energy production or giving the same energy production with smaller collector area.

Keywords: Solar energy, thermal solar collectors, evacuated tube, series and parallel configurations, tests

---

1. Introduction

Solar radiation is the main source of the energy system of the Earth and it is the basis of all the natural cycles and events of life, including many human activities. The knowledge of how the radiation is

---

** Corresponding author. Tel.: +39 06 377251
E-mail address: e.bocci@unimarconi.it.

doi:10.1016/j.egypro.2015.11.804

intercepted(absorbed or deflected) by the atmospheric layer that surrounds the Earth (the fraction of it that reaches the ground and the one that comes from all directions)is a prerequisite for the understanding of natural phenomena related with climate and meteorology and the location and design of the systems that use solar energy. The use of new forms of renewable energy, including solar, in the future will become increasingly necessary to ensure the energy needs while avoiding the environmental impact caused by the massive use of fossil fuels [1–4].As claimed by Oussama Ibrahim et al. [5], energy demand is continuously increasing due to global population growth and improved living standards. However, fossil fuels, the current primary energy source, are being consumed in a random increasing manner, even though they are non-renewable and they are not distributed equally in the earth. Consequently, environmental pollution, economic and energy security issues are fearfully increasing. Based on this fact, worldwide governments are working hard to raise the share of renewable energy sources and reduce energy consumption. Different energy approaches have been proposed for various cases such as energy conservation building codes, low energy buildings, ultra-low energy buildings, zero energy buildings and energy-plus buildings. Water heating is a major energy consumer all around the world. Water issues such as quality monitoring [6,7] and management, water heating [8–11], purification [12–14] are major energy and exergy issues for producers and consumers all around the world [15–20]. Kalogirou presented the various types of solar thermal collectors and applications [21].In reference to the report published in June 2014 [22], the European solar thermal market decreased in 2013, as shown in Table 1 (the data are referred to the most installed and in operation collector type: the glazed). Contrary to what happened in previous years, when there were significant variations between markets, the downturn in 2013 affected almost all of the largest and medium size markets (Flat plate and Glazed). The main markets declined or, at best, stagnated. In particular, the Italian solar thermal market was characterized by a difficult start due to the economic crisis and uncertainty with the legislative framework. Only in the last quarter of 2013 were signs of market recovery. The law No. 90 of 2013 (August) modified the tax deductions for energy efficiency measures in buildings, increasing the deductible share to 65% of the investment costs over 10 years.

Table 1. Installed and in operation glazed solar collectors

Country	Market (=Newly Installed m^2)				In operation m^2	
	2011	2012	2013	2013/12	2013	2013/12
Italy	390,000	330,000	297,000	-10%	3,649,130	8.4%
EU28+Swiss	3,689,499	3,457,915	3,051,543	-11.8%	43,109,543	6.2%

The vacuum tube collectors have been extensively studied and there are many researches in the scientific literature: Li et al. [23] established a heat transfer model for a system of solar collectors in forced circulation; Kim and Seo investigated the thermal performance of a glass evacuated tube solar collector [24]; Morrison at al. studied different methods to extract heat from evacuated tubes [25]; Badar et al. investigated the overall heat loss coefficient [26]; Glembin at al. studied the impact of low flow rates on the efficiency of coaxial vacuum tube collectors [27]; Morrison at al. evaluated the characteristics of water-in-glass evacuated tube solar heaters [28] and developed a model for natural circulation flow rate through tubes mounted over a diffuse reflector [29]; Budihardjo and Morrison also evaluated the performance using measurements of optical and heat loss characteristics [30]; Shah and Furbo. investigated heat transfer and flow structures by means of CFD model [31].During the phase of design, study and calculation of the performance of the collectors system we referred to the work developed by Kaci et al. [32], Chen et al. [33], Giovannetti et al. [34], Fischer et al. [35], Zambolin and Del Col [36][37], Hayek et al. [38], Sakhrieh et al. [39], Föste et al. [40], Handoyo et al. [41], Liang at al. [42], Ma et al. [43], Stanciu C. and Stanciu D. [44], Tang et al. [45], paying attention to the specific test conditions and standards adopted in their researches. In particular the European standard UNI-EN 12975-02 describes the methodologies for characterization of the thermal performance of solar collectors. The main objective of this study is to analyze an innovative configuration of a system of three vacuum U-tube solar collectors in order to determinate the thermal efficiency, comparing the results of the two different configurations: series and parallel.

2. Experimental setup

2.1. Collector specification

An innovative prototype of evacuated tube solar thermal collector has been tested.T he prototype differs from the standard prototypes because has a third integrated pipe that allows parallel connection of multiple modules easy as the series connection. In fact, for installations of the same nature with modules belonging to the same market segment, collectors are commonly installed in series to avoid hydraulic complications. In particular enables up to 4-5 solar collectors to be connected, without the return line, with a unique hot water line and a unique cold water line. T he studied collector consists of eighteen 58 mm diameter borosilicate double air-casing vacuum tubes fixed in an anodized aluminium framework for strength. Direct and diffused solar radiation penetrates the outside of the tubes and it is captured in the absorber. A special aluminium absorber inside the glass tube transfers the heat to the copper U tube inside the tubes. The collector specification is showed in Table 2.

Table 2.Collector specification

Collector specification	Measurement Units	Dimensions
Measurements (lenght x width x height)	[mm]	2002x1712x120
Gross Area	[m2]	3.427
Aperture Area	[m2]	1.80
Absorber Area	[m2]	1.46
Weight (Empty)	[kg]	86.5
Fluid content	[l]	3.09
Max Pressure	[kPa]	1000
Recommended flow range	[l/min*m2]	0.8 (1.45 for collector)
Absorption coefficient	[%]	< 94.5 ±2
Coefficient transfer of the glass	[%]	< 91.5 ±1
Connecting dimensions	[inch]	6 x ¾''-M

In order to assess the performance of the collector, a forced-circulation solar water heating system has been built. The test circuit was realized according to the UNI-EN 12975-2 requirements.

Both configurations, parallel and series, were performed with a forced circulation closed circuit. The test circuit consists of the following components: two storage tanks of **300 l** (cold water) and **200 l** (hot water, heated by electric resistance), a thermostatic mixer valve (setting range: 308K-338 K) for mixing the two flows and in order to obtain a predetermined input temperature at the solar collectors system; the flow control valve, located between the mixer and the pump; a WiloST15/6-3, 230VAC, 50Hz circulation pump, with3power regulation (43-61-82W); two flow meters; manometers, safety valves, an expansion tank, insulated copper pipes.

2.2. Sensors and data acquirement

The sensors used are:

- thermocouples(typeJ, made of Iron(+) and constantan(Cu-Ni) (-), sensitivity of51.7microvolts/°C);
- pyranometer(LPPYRA03AV, Delta Ohm second class, spectral range: 305nm÷2800nm, typical sensitivity: 10microV/(W/m2), measuring range: 0 to2000 W/m2);
- anemometer (Gill Wind Sonic, range: 0-60m/s; accuracy: +/-2%; resolution: 0.01m/s, wind direction range: 0-359; accuracy: +/-3% @12m/s; resolution: 1).
- flow transmitter (Vortex, range 0.9 – 15lt / min; Accuracy 1%).

The temperature values given by the thermocouples were acquired with a National InstrumentsFieldPointCFP-1808. The software "Measurement and Automation", for data acquisition, and "Labview", for data recording have been used.

The values provided by Anemometer and Solar imeter were acquired with ArduinoDue, configured with the software "CoolTerm".

2.3. Test Conditions

The system of 3 collectors has been repeatedly tested in its range of operating temperatures, under clear skies, in order to determine its performance in two configurations: Series and Parallel.

The system has been tested in steady state condition, according with the UNI-EN 12975-2 that demands the requirements shown in Table 3 below.

Table 3.Steady State Condition of UNI EN 12975-2

Parameters	Range
G	$\pm 50\ W/m^2$
T_{amb}	$\pm 1{,}5\ K$
$Q_{in}\ (kg/s)$	$\pm 1\%$
T_{in}	$\pm 0{,}1°K$

Table 4. Testing Condition

Preconditioning	15’
Time single test	10’
Radiation	> 850W
Operating pressure	$2 \cdot 10^5 Pa$ (2,0 bar)
Flow specific heat	4181 $J/(kg \cdot K)$
Acquisition frequency	1 data per second

It has been planned the testing condition showed in Table 4 below (e.g. the pre- conditioning time of 15 minutes proved to be enough time for the system to reach operating conditions and do not have influences due to the inertia of the system).

Regarding the flow rate of the fluid in the closed circuit, the tests were carried out in such a way as to compare the two systems in two different conditions:

series inlet flow rate identical to the total parallel flow rate (e.g. with specific flow rate of 1.25 l/min this meaning 1.25 x 1.472(opening area) x 3 (number of collectors) = 5.52 l/min).

same flow rate in the single panel (i.e. inlet flow rate to the parallel equal to three times the series one; e.g. with a specific flow rate of 0.7 l/min, it results series = 0.70*1.472*3 = 3.091 l/min, parallel = 3*3.091 = 9.27 l/min)

The general characteristics of each test are resumed in Table 5 below.

Table 5. Test conditions

Parallel configuration		Series configuration	
Q=5.5 l/min	Q=9.3 l/min	Q=3.1 l/min	Q=5.5 l/min
T=293 K	T=293 K	T=293 K	T=293 K
T=308 K	T=308 K	T=308 K	T=308 K
T=323 K	T=323 K	T=323 K	T=323 K
T=338 K	T=338 K	T=338 K	T=338 K

The different test conditions allow to evaluate the performances of the system in the two different configurations(series/parallel) with a direct comparison.

3. Results and Conclusion

For each fluid temperature in input and for each flow rate, the efficiency was calculated as the ratio of the output power and the input power:

$$\eta = \frac{P_{out}}{P_{in}} \tag{1}$$

The input power P_{in} is the product of radiation G and the aperture area A, exposed to the radiation:

$$P_{in} = G \cdot A \tag{2}$$

The output power represents the heat(per time unit) exchanged to the heat-transfer fluid, which is proportional to the difference between input and output fluid system temperatures (DT), the flow rate (Q), density of the fluid (ρ), the fluid specific heat (c), :

$$\Delta T = T_{out} - T_{in} \tag{3}$$

$$P_{out} = \rho \cdot Q \cdot c \cdot \Delta T \tag{4}$$

The curve of instantaneous efficiency for each configuration was calculated, as claimed by the Standard UNI-EN 12975 (a1 and a2 are the linear and quadratic heat loss coefficient), setting an approximation of the data collection to the Ordinary *Least Squares*:

$$\eta = \eta_0 - a_1 T_m^* - a_2 I (T_m^*)^2 \tag{5}$$

where:

$$T_m^* = (T_m - T_{amb})/G \tag{6}$$

and:

$$T_m = (T_{out} - T_{in})/2 \tag{7}$$

The efficiency values in function of Tm are showed in the Figure 1 below.

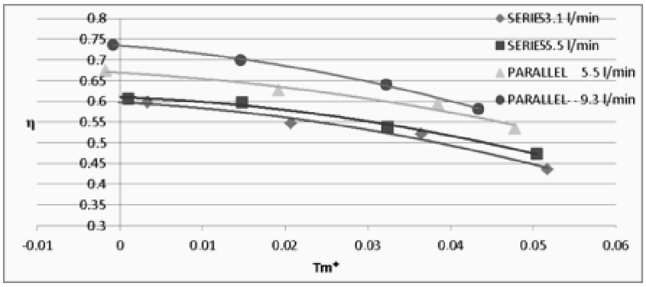

Fig. 1. Efficiency variation versus Tm

The Figure 1 shows that, as foreseen from literature and from equation 5, the efficiency decreases with the increase of Tm. Also, as foreseen from literature and from equation 1 and 4, the efficiency increases with the increase of the flow Q. Regarding the evaluation of the efficiency with the same flow rate in the single panel (i.e. series 3.1 and parallel 9.3 l/min), Figure 1 shows that not only the parallel efficiencies are higher (in particular from 20 to 40%) owing to the higher flow but also owing to the inferior output temperature and so lower Tm. Regarding the evaluation of the efficiency with the series inlet flow rate identical to the total parallel flow rate (i.e. series and parallel 5.5 l/min), Figure 1 shows that the parallel efficiencies are higher (in particular from 10 to 30%) but this cannot be accounted directly to the inferior output temperature because, at same time, the Tm values are also higher in the parallel configuration respect to the series. This meaning that within these prototypes something happen in the circulation of the water that cannot configure the collector as pure parallel configuration.

In conclusion, the tests show, as foreseen from literature and from equations, that the parallel configuration can gives higher efficiency. Therefore, these prototypes, facilitating the parallel configuration, that increases the efficiency, canincrease the overall energy production or give the same energy production with smaller collector area (if applied in parallel instead of series configuration). But, the possibility to have an increase of efficiency without a loss of the quality of the energy produced, i.e. the reduction of the output temperature, has not registered with the same flow rate. In particular, the tests show that, with same flow, the performance of the collectors in the different series/parallel configuration follows the predictable series/parallel performance (i.e. increase of efficiency but reduction of output temperature in parallel configuration). Where the most applied case is considered, i.e. total flow fixed for the two configurations, the predictable higher efficiency of the parallel configuration is confirmed but, in this case, not, or at least not always, the inferior output temperature. To explaining the superior output temperature a simulative and experimental campaign at the level of each single panel and single tube has to be envisaged in order to verify if the temperature and/or the pressure drop difference can reduce the flow in a collector or part of a collector, explaining the superior temperatures and if these different fields of temperatures and flows can effectively guarantee higher efficiencies without remarkable temperatures decrease.

Acknowledgements

The support of the thesis student Federico Giorgini, Sapienza university of Rome, Interuniversity Research Center for Sustainable Development (CIRPS), Lazio Region and Pleion Ltd. is kindly acknowledged.

References

[1] Naso V, Bocci E, Orecchini F, Marcelo D. Renewable Resources to Hydrogen: Appropriated Technologies for Developing Countries. Renew Energ Cent Asia Ctries Econ Environ Soc Impacts 2005:95–101.

[2] Bocci E, Zuccari F, Dell'Era A. Renewable and hydrogen energy integrated house. Int J Hydrog Energy 2011;36:7963–8.

[3] Falvo MC, Martirano L, Sbordone D, Bocci E. Technologies for Smart Grids: a brief review, Wroclaw, Poland: 2013.

[4] Bocci E, Sisinni M, Moneti M, Vecchione L, Di Carlo A, Villarini M. State of Art of Small Scale Biomass Gasification Power Systems: A Review of the Different Typologies. Energy Procedia 2014;45:247–56.

[5] Ibrahim O, Fardoun F, Younes R, Louahlia-Gualous H. Review of water-heating systems: General selection approach based on energy and environmental aspects. Build Environ 2014;72:259–86.

[6] Pietrelli A, Micangeli A, Ferrara V, Raffi A. Wireless Sensor Network Powered by a Terrestrial Microbial Fuel Cell as a Sustainable Land Monitoring Energy System. Sustainability 2014;6:7263–75.

[7] Micangeli NIA. Monitoring of large size solar thermal systems: Design and data analysis 2012.

[8] Micangeli A, Michelangeli E, Naso V. Sustainability after the thermal energy supply in emergency situations: The case study of Abruzzi Earthquake (Italy). Sustainability 2013;5:3513–25.

[9] Villarini M, Bocci E, Moneti M, Di Carlo A, Micangeli A. State of Art of Small Scale Solar Powered ORC Systems: A Review of the Different Typologies and Technology Perspectives. Energy Procedia 2014;45:257–67.

[10] Micangeli A, Evangelisti S, Sbordone D. Alternative energy: Solar thermal energy 2013.

[11] Borello D, Corsini A, Delibra G, Evangelisti S, Micangeli A. Experimental and computational investigation of a new solar integrated collector storage system. Appl Energy 2012;97:982–9.

[12] Dell'Era A, Zuccari F, Santiangeli A, Fiori C, Micangeli A, Orecchini F. Energy optimisation and layout of a membrane-free OSEC system for the hypochlorite self-production in Developing Countries. Energy Convers Manag 2013;75:446–52.

[13] Micangeli A, Grego S, Esposto S. Sustainable Rehabilitation of Water Infrastructures in Southern Iraq After theSecond Gulf War. Handb. Sustain. Eng., Springer; 2013, p. 211–45.

[14] Micangeli A, Esposto S. Post-earthquake rehabilitation of the rural water systems in Kashmir's Jehlum Valley. Disasters 2010;34:684–94.

[15] Pietrelli A, Ferrara V, Micangeli A, Uribe L. Efficient energy harvesting for Microbial Fuel Cell dedicated to Wireless Sensor Network. AISEM Annu. Conf. 2015 XVIII, IEEE; 2015, p. 1–4.

[16] Gambino V, Micangeli A, Naso V, Michelangeli E, Mario LD. A Sustainable and Resilient Housing Model for Indigenous Populations of the Mosquitia Region (Honduras). Sustainability 2014;6:4931–48.

[17] Micangeli A, Iannuzzo N, Esposto S. Chlorine self-production plant solution for effluent water to be used in irrigation in gaza strip. Handb. Sustain. Eng., Springer; 2013, p. 117–36.

[18] Micangeli A, Naso V, Michelangeli E, Matrisciano A, Farioli F, Belfiore NP. Attitudes toward Sustainability and Green Economy Issues Related to Some Students Learning Their Characteristics: A Preliminary Study. Sustainability 2014;6:3484–503.

[19] Bocci E, Villarini M, Bove L, Esposto S, Gasperini V. Modeling Small Scale Solar Powered ORC Unit for Standalone Application. Math Probl Eng 2012;2012.

[20] Villarini M, Bocci E, Di Carlo A, Sbordone D, Falvo MC, Martirano L. Technical-Economic Analysis of an Innovative Small Scale Solar Thermal-ORC Cogenerative System. Comput. Sci. Its Appl. 2013, Springer; 2013, p. 271–87.

[21] Kalogirou SA. Solar thermal collectors and applications. Prog Energy Combust Sci 2004;30:231–95.

[22] Solar Thermal Markets in Europe n.d.

[23] Li Z, Chen C, Luo H, Zhang Y, Xue Y. All-glass vacuum tube collector heat transfer model used in forced-circulation solar

water heating system. Sol Energy 2010;84:1413–21.

[24] Kim Y, Seo T. Thermal performances comparisons of the glass evacuated tube solar collectors with shapes of absorber tube. Renew Energy 2007;32:772–95.

[25] Morrison GL, Budihardjo I, Behnia M. Water-in-glass evacuated tube solar water heaters. Sol Energy 2004;76:135–40.

[26] Badar AW, Buchholz R, Ziegler F. Experimental and theoretical evaluation of the overall heat loss coefficient of vacuum tubes of a solar collector. Sol Energy 2011;85:1447–56.

[27] Glembin J, Rockendorf G, Scheuren J. Internal thermal coupling in direct-flow coaxial vacuum tube collectors. Sol Energy 2010;84:1137–46.

[28] Morrison GL, Budihardjo I, Behnia M. Measurement and simulation of flow rate in a water-in-glass evacuated tube solar water heater. Sol Energy 2005;78:257–67.

[29] Budihardjo I, Morrison GL, Behnia M. Natural circulation flow through water-in-glass evacuated tube solar collectors. Sol Energy 2007;81:1460–72.

[30] Budihardjo I, Morrison GL. Performance of water-in-glass evacuated tube solar water heaters. Sol Energy 2009;83:49–56.

[31] Shah LJ, Furbo S. Theoretical flow investigations of an all glass evacuated tubular collector. Sol Energy 2007;81:822–8.

[32] Kaci K, Merzouk NK, Merzouk M, Hakem SA. Effect of Tests Norms on the Instantaneous Efficiency of a Plate Solar Collector. Procedia Eng 2012;33:392–403.

[33] Chen Z, Furbo S, Perers B, Fan J, Andersen E. Efficiencies of Flat Plate Solar Collectors at Different Flow Rates. Energy Procedia 2012;30:65–72.

[34] Giovannetti F, Kirchner M, Kliem F, Hoeltje T. Development of an Insulated Glass Solar Thermal Collector. Energy Procedia 2014;48:58–66.

[35] Fischer S, Heidemann W, Müller-Steinhagen H, Perers B, Bergquist P, Hellström B. Collector test method under quasi-dynamic conditions according to the European Standard EN 12975-2. Sol Energy 2004;76:117–23.

[36] Zambolin E, Del Col D. Experimental analysis of thermal performance of flat plate and evacuated tube solar collectors in stationary standard and daily conditions. Sol Energy 2010;84:1382–96.

[37] Zambolin E, Del Col D. An improved procedure for the experimental characterization of optical efficiency in evacuated tube solar collectors. Renew Energy 2012;43:37–46.

[38] Hayek M, Assaf J, Lteif W. Experimental Investigation of the Performance of Evacuated-Tube Solar Collectors under Eastern Mediterranean Climatic Conditions. Energy Procedia 2011;6:618–26.

[39] Sakhrieh A, Al-Ghandoor A. Experimental investigation of the performance of five types of solar collectors. Energy Convers Manag 2013;65:715–20.

[40] Föste S, Giovannetti F, Ehrmann N, Rockendorf G. Performance and Reliability of a High Efficiency Flat Plate Collector – Final Results on Prototypes. Energy Procedia 2014;48:48–57.

[41] Handoyo EA, Ichsani D, Prabowo. The Optimal Tilt Angle of a Solar Collector. Energy Procedia 2013;32:166–75.

[42] Liang R, Ma L, Zhang J, Zhao D. Theoretical and experimental investigation of the filled-type evacuated tube solar collector with U tube. Sol Energy 2011;85:1735–44.

[43] Ma L, Lu Z, Zhang J, Liang R. Thermal performance analysis of the glass evacuated tube solar collector with U-tube. Build Environ 2010;45:1959–67.

[44] Stanciu C, Stanciu D. Optimum tilt angle for flat plate collectors all over the World – A declination dependence formula and comparisons of three solar radiation models. Energy Convers Manag 2014;81:133–43.

[45] Tang R, Gao W, Yu Y, Chen H. Optimal tilt-angles of all-glass evacuated tube solar collectors. Energy 2009;34:1387–95.

Biography

Enrico Bocci. Born in Rome, Italy, in 1975. M.S. in mechanical engineering, Ph.D.in Energy System and Research Assistant at Sapienza University. Since 2009 Assistant and since 2015 Associate Professor at Marconi University. Author of 3 books, 22 articles, 1patent. Research interests: gasification, solar and fuel cells power plants and power trains.