MEDIUM TEMPERATURE PTC COLLECTOR: EXPERIMENTAL ANALYSIS AND PERFORMANCE

Chiara Cinelli, Maurizio De Lucia, Paolo Giovanetti, Christian Paolo Mengoni, Stefano Toccafondi

Department of Energy Engineering "Sergio Stecco" Florence University, via di S. Marta 3 50139 Florence

ABSTRACT

The current worldwide energy condition, impose to reduce by 20% the CO_2 emissions (Kyoto Protocol). The development of systems that use renewable sources in a sustainable and realistic way can reduce fossil fuel consumption and CO_2 emissions. The use of solar thermal applications can completely fulfil the 20-20-20 European directives with an important contribution to the decrease of greenhouse gas emissions. In this context, the Departmento of Energy Engennering "Sergio Stecco" is developing an integrated solar systems for solar heating (SH), solar heating and cooling (SHC) applications and heat for industrial process. This activities concerns the development and the fulfilment of prototypes of Parabolic Trough Collectors (PTC) focused on the conversion of solar radiation to heat at medium temperature (<200°C). These activities are involved in many European, national and regional research projects. To estimate the performance and sustainability of these solar-thermal applications, a test rig has been realized.

INTRODUCTION

A convenient use of solar energy meets quite well target of 20-20-20 European directives: primary energy saving, reduction of CO_2 emissions and, obviously, the use of renewable energies [1], [2].

Nowadays, solar thermal systems at low temperature are a standard application to exploit solar radiation for home heating and cold water production, while the use of solar energy at medium temperature, that could well satisfy residential cooling or industrial process heat and cooling demand [3] is still scarcely widespread and systems realized are mostly prototypes.

On the other hand, industrial sector has the largest energy consumption in the OECD countries, at approximately 30% compared to energy consumption of transportation, household and service sectors. Just one third of this energy demand is related to electricity, but two thirds are related to heat below 250°C [4]. For these reasons, medium temperature solar thermal applications could give an appreciable contribution in fossil fuel consumption reduction.

Solar concentration seems to be an interesting method for development of sustainable medium and high temperature systems. Today, research is mostly focused on Concentrated Solar Power (CSP), for 450-550°C heat production. This application represents the actual highest technology for solar thermal applications, however sustainability in term of cost, duration and performance today should be deeply investigated.

With a medium temperature target (150-250°C) concentration ratio and consequently form tolerance could be reduced allowing the use of simplified systems and, as a consequence, cost reduction: less expensive materials and surface treatments, less production and assembling cost, simpler control systems.

Parabolic through collector (PTC) is an interesting solution for medium temperature solar production; these systems were born for CSP applications, but recently smaller PTCs for medium temperature have been studied and developed [2].

In this context, at Department of Energy Engineering "Sergio Stecco" some PTC prototypes for small scale, medium temperature applications, optimized for SHC (up to 200°C), marked by low value of cost/performance ratio, are in development.

Nowadays on literature different kind of PTC for medium temperature [4] are available. All systems presented are characterized by thermal loss and standard optical performance; on the other hand one axes tracking PTC's are sensitive to the incident angle, and for many CSP systems this effects are demonstrate [5], [6]. This influence is certainly greater on medium temperature PTC, where geometry and layout of collectors cause shading and other negative effects more than CSP collectors.

This paper shows a method for estimate performance reduction caused by the incidence angle and the characterization of the PTC developed. In accordance with [5] and most common collectors an incident angle modifier (IAM) parameter has been defined. Method presented uses experimental data obtained with many isothermal, steady-state daily tests realized using a test rig developed and realized at Department of Energy Engineering "Sergio Stecco". This method uses data with high radiation because at low radiation (<300 W/m^2) steady-state can't be reached. This condition is good for the proposed analysis because radiation and incidence angle appear to be independent and so IAM is unaffected by radiation and temperature fluctuations. However a constant radiation condition is required and, in accordance with [5], [4], [6], PTCs denote little influence for radiations over 500 W/m^2. For this reason, it is possible consider iso-radiation data intervals of 50 W/m^2 over 500 W/m^2 of direct normal incidence radiation.

Characterization presented is focused to estimate the prototype performances for SHC applications and heat for industrial process production; the test rig used is N/S oriented at latitudes near 40° (Florence latitude). Results of this paper allow a characterization of the first PTC prototype realized. These results are fundamental for estimate thermal energy production and define the plant's performances in the real working conditions of the prototype.

Heat production and solar cooling require different layouts of solar field for maximize energy collection [7], but also incidence angle changes its trend. For this reason, IAM is necessary to make correct and exhaustive sizing of a solar fields.

Incident angle results from latitude, seasonal nature, and orientation of tracking axes and slope; trend of incident angle at Florence latitude for a N/S oriented PTC is shown in Fig. 1.

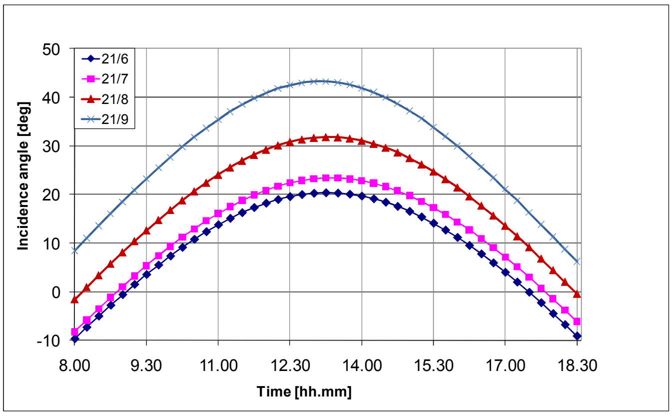

Fig. 1: Incidence angle at Florence latitude on summer

Fig. 1 shows a maximum of incidence angle at solar noon and a zero-incidence angle obtainable only for some months, in the midmorning and in the afternoon. An E/O orientation allows a zero incidence angle at solar noon, but a 90 degree incidence angle for azimuth angle near sunrise and sunset.

TEST RIG

Solar collector

PTC tested are completely developed at Energy Department "Sergio Stecco"[8]. Prototype is a PTC, with near 40 m^2 of total active surface and a concentration ratio of 37 for a fluid temperature up to 180°C.

Fig. 2: PTC developed at Department "S. Stecco"

Reflectors have less than 1mm manufacture's tolerances: this solution is in accordance with [9].

Receiver is a non-evacuated glass tube with a selective ceramic coating [10]. Design of receiver is the best arrangement between thermal loss and optical collection [8].

The tracking system is driven by a frequency controlled asynchronous motor. Tracking control is composed by an optical sensor (fine pointing) and a time algorithm *pointing*. Time algorithm is also used for calculate "solar properties" like azimuth, elevation and incidence angle (φ) in data reduction.

Test Rig

Fig. 3 shows the P&I of the test rig: a pressurized (12 bar) loop circuit and a dissipation one, both feed by water. The loop circuit can reach a maximum temperature of 180°C. It is composed by a circulation pump driven by an inverter, a 3-way valve for temperature regulation and an expansion tank used to compensate the fluid thermal expansions. The plate heat exchanger allows to control temperature with a 150 m^3 water storage, simulating a thermal load.

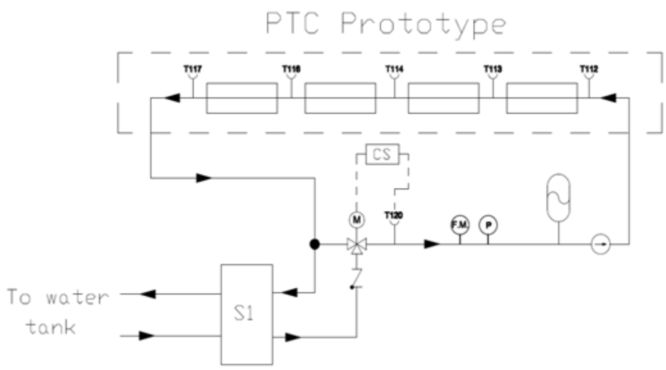

Fig. 3: Test rig's P&I

The P&I shows instrumentation to measure the prototype performances: flowmeter, pressure transducer and temperature sensors. The ambient temperature and the solar radiation are also measured. All instruments uncertainty are in accordance with IEA SHC Task 38 guidelines [11].

DATA ACQUISITIONS AND REDUCTIONS

Thermal power (Q) is measured with a stationary method in accordance with [5], [12].

Reduction of beam radiation

The direct normal irradiation to ground (I_n) is calculated as the difference of measurements made by two piranometers for normal to ground global (G_n) and diffuse radiation (D).

For evaluating PTC efficiency the direct normal radiation to the collector (I_p) is needed:

$$I_p = \frac{I_n}{\sin\psi} = \frac{G_n - D}{\sin\psi} \quad (1)$$

where ψ is the rotational angle of the parabola when it is in focused tracking mode; ψ values are collected during measurements.

I_p could be also calculated as:

$$I_p = \frac{I_n \cos\varphi}{\sin\alpha} \tag{2}$$

where α and φ are radiations and incidence angle estimated by time algorithm while in eq. (1) all data came from experimental campaign.

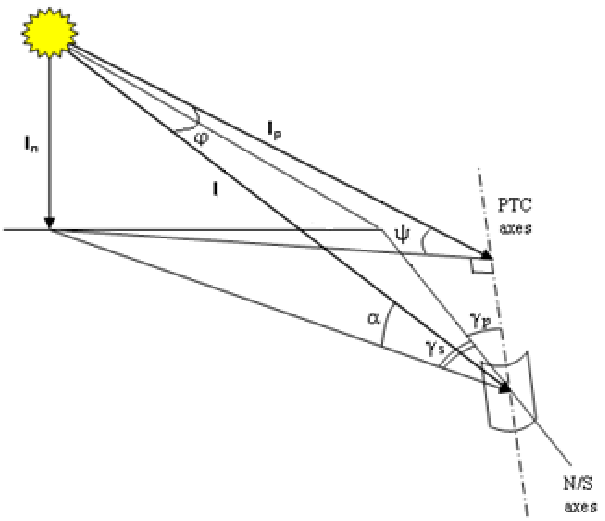

Fig. 4: Correction diagram for misalignments from N/S axes

Measuring thermal power (Q) and direct normal radiation (I_p), the collection efficiency is calculated as:

$$\eta = \frac{Q}{I_p S_c} \tag{3}$$

where S_c is the collection surface.

RESULTS

All daily tests realized are filtered from, transient and unsteadies in accordance with [5]. All samples processed are collected in a database and all efficiency data available are arranged for I_p, T_m-T_a (ΔT) and φ respectively.
Fig. 5 shows the experimental data collected for different radiation levels, at three different ΔT levels and four values of incidence angles

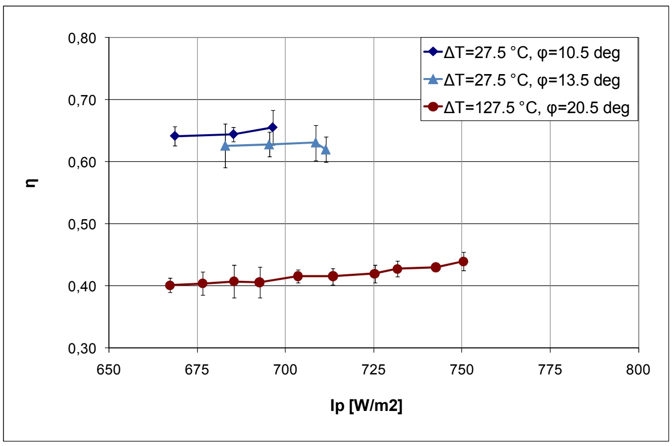

Fig. 5: Influence of I_p

Fig. 5 shows and confirms a weak influence of I_p on PTC efficiency at high radiations: especially for values over 650 W/m^2.
For data over 650 W/m^2 the values of efficiency do not depend on irradiation, so in that range variation depends on other parameters. In Fig. 6 the dependence on incidence angle is shown; values are referred to data collected on irradiation range between 650-700 W/m^2. Efficiency reduction due to incidence could reach values up to 30%.

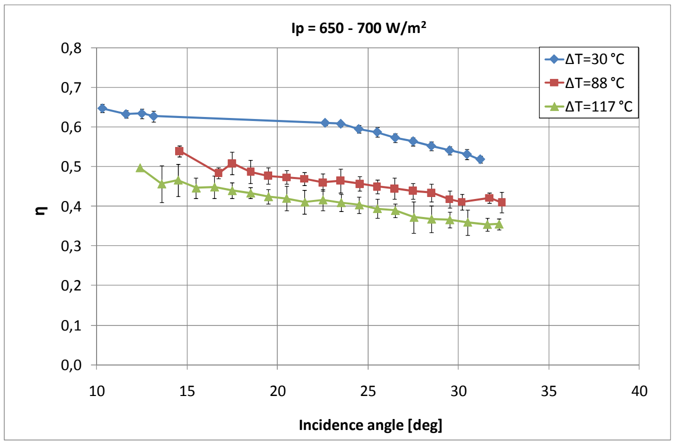

Fig. 6: Influence of φ

In the same way, dependence on ΔT is reported in Fig.7.

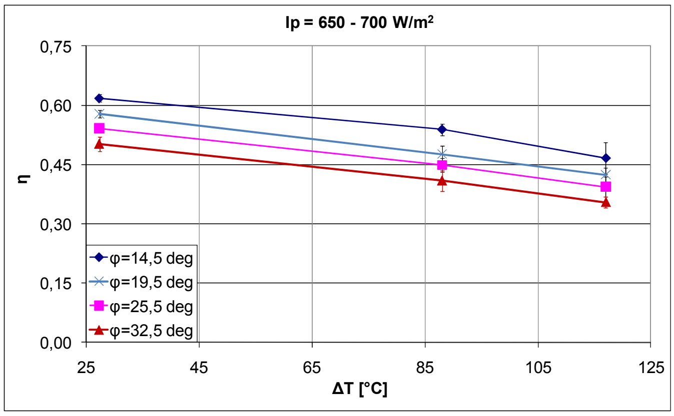

Fig. 7: Influence of ΔT

This trend confirm a great influence of ΔT and φ on the PTC's performances, however ΔT and φ don't have respective interactions.
For this reason, an incidence reduction is possible, defining a $\eta_{r\varphi}$ in this way:

$$\eta_{r\varphi} = \frac{\eta_{\varphi=i,\Delta T=j}}{\eta_{r\varphi=i,\Delta T=ref}} \tag{4}$$

This reduction is applied to all samples represented on Fig. 7, where $\eta_{\varphi=i}$ is a constant-radiation (I_p=650-700 W/m^2), at the i-th incidence value and the j-th value of ΔT. $\eta_{\varphi=i,\Delta T=ref}$ is the reference value of ΔT equal to 27°C degree, at the i-th value of φ.
Results for $\eta_{r\varphi}$ are show on Fig. 8:

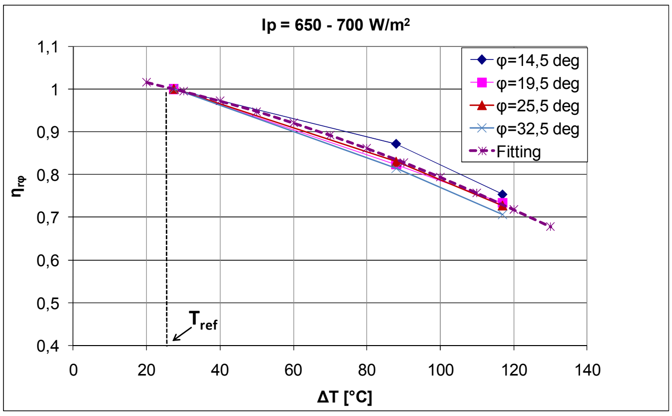

Fig. 8: Definition of φ-reduced efficiency vs ΔT

An incidence-reduced and constant-radiation curve is defined by the fitting of previous data.

Consequently, the polynomial is used for a temperature-reduction of data in the range 650-700 W/m^2:

$$\eta_{r\Delta T} = \frac{\eta}{a\,\Delta T^2 + b\,\Delta T + c} \qquad (5)$$

Where η is the performance data between 650 and 700 W/m^2 .

In Fig. 9 are represented all the constant-radiation and temperature reduced data available from experimental tests; all $\eta_{r\Delta T}$ calculated points are used to define another 2° order polynomial. This temperature-reduced and constant-radiation curve permit to define the incident angle modifier. In the database there aren't zero-incidence data to refer our IAM at zero-incidence value. For this reason, an incident angle modifier (IAM_{10}), referred at 10 degrees of incident angle is defined:

$$IAM_{10} = \frac{\eta_{r\Delta T,\varphi=i}}{\eta_{r\Delta T,\varphi=10}} \qquad (6)$$

Where $\eta_{r\Delta T\varphi=i,}$ is a value at the i-th value of incidence of the temperature-reduced fitted curve.

The results of characterization are reports in Fig.9 in terms of $\eta_{r\Delta T}$ and IAM_{10}.

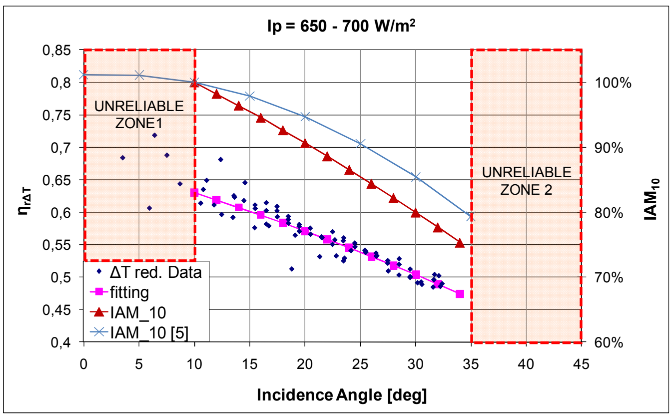

Figure 9: Definition of IAM_{10} and comparison with [5]

In the graph there are two unreliable zones depend on the few data available for a good characterization in that range of incidence. The experimental tests carried out on summer, shows incidence angles from 10 to 35 degrees (see Fig.1). Other tests that will be carried out in other months will allow to reduce unreliability to lower and higher incidence angles.

Moreover Fig. 9 shows the results in terms of IAM_{10}. There is a comparison with some PTC collectors (SEGS-LS2 [5]) for CSP; characterized in terms of IAM. In this graph, IAM for SEGS-LS2 is reduced as IAM_{10}. There is a maximum difference of 6%, it could be considered a very good results for a medium temperatre collector compared with a CSP one.

CONCLUSION

A characterization of medium temperature PTCs is presented. The method used in term of tests, analysis and procedures is focused to characterization of φ and ΔT influences on the efficiency of PTC. Test rig developed can be use to estimate the global performance of a medium temperature PTC in real work condition to subsequently characterize the system global performance.

The PTC prototype shows range of global efficiency from 65% to 45% for incidence angle from 10 to 35. For this reason, influence of φ on the PTC efficiency must be considered. IAM is a fundamental parameter for simulations and sizing of solar concentrated systems.

A comparison with high performances, big scale PTC (SEGS-LS2), developed for CSP applications shows a good working of our prototype. The form tolerance, the non-evacuated solution and the cost/efficiency balanced coating allow a considerable cost reduction, against a small efficiency reduction for medium temperature applications.

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NOMENCLATURE

Symbol	Quantity	SI Unit
I_n	Normal to ground direct radiation	W/m^2
G_n	Normal to ground global radiation	W/m^2
D	Diffuse radiation	W/m^2
I_p	Direct normal incident radiation	W/m^2
ψ	Parabola angle	Deg.
φ	Incidence angle	Deg.
α	Solar elevation	Deg.
Q	Thermal power	W
S_c	Collection area	m^2
η	Efficiency	-
T_m	Average water temperature	°C
T_a	Ambient temperature	°C
ΔT	Tm-Ta	°C
$\eta_{r\varphi}$	Incidence-reduce efficiency	-
$\eta_{r\Delta T}$	ΔT-reduce efficiency	-

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