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ScienceDirect

Energy Procedia 48 (2014) 1217 – 1225

Energy Procedia

SHC 2013, International Conference on Solar Heating and Cooling for Buildings and Industry
September 23-25, 2013, Freiburg, Germany

Monitoring of a MW class solar field set up in a brick manufacturing process

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Abstract

InSun is an FP7 project that aims to demonstrate the reliability and quality of large solar thermal collector fields to produce industrial process heat at different temperature levels. In three demonstration plants, MW class solar fields with concentrating (Fresnel and parabolic trough) and flat plate collectors are installed, supplying heat to different production processes, at diverse climatic conditions. The new plants will be monitored to assess the performance and optimize the control strategies of the solar installations. One of the demonstration plants is a brick production company located in Italy (Laterizi Gambettola S.r.l.), where the installation of Fresnel collectors is foreseen, to reduce the consumption of natural gas, currently employed for the generation of process heat.

After planning and commissioning, the solar field is now being monitored. Results in terms of temperatures, mass flows and control procedures are supervised to evaluate components' performance and system energy balances. A dedicated procedure is under development, suitable for handling with the huge amount of data available thanks to the monitoring campaign.

This paper presents a description of the solar energy integration into the brick production process and of the installed monitoring network. The data analysis procedure is also presented.

Selection and peer review by the scientific conference committee of SHC 2013 under responsibility of PSE AG

Keywords: Large Scale Solar Thermal; Fresnel collectors; BIN Method Analysis.

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doi:10.1016/j.egypro.2014.02.138

1. Introduction

A reliable operation of the production process is key for manufacturers. Therefore, engineers dealing with large solar thermal collectors fields delivering heat to industrial processes can only rely on proven and standardized solutions, with payback times not longer than 5 years.

Starting from these considerations, the main objective of the InSun project is to demonstrate the reliability, efficiency and quality of three large scale industrial applications with process heat supply at different temperature levels, in different climatic conditions. The solar collector technologies demonstrated range from improved flat-plate collectors for process heat up to 95°C, to tracked concentrating collectors (Linear Fresnel Collectors and Parabolic Trough Collectors) to supply medium temperatures between 160 and 250°C [1]. Within the project the research focuses on the analysis and optimization of the integration process of the solar systems, on the performance monitoring and on the control optimization of the solar thermal systems in combination with the industrial processes involved.

2. Industrial process and solar field integration

2.1. Existing brick manufacturing process

The brick manufacturing process involves a number of operations where heat is required. The raw material is first processed and mixed, then it is extruded and finally the bricks are dried before being fired in a tunnel kiln. Both processes are fed with natural gas vein burners, and the necessary hot air flows are then finely regulated with fans and with internal recirculation ducts, which directly heat up the air at the desired temperatures.

The drying and cooking continuous processes are schematically shown in Fig. 1, where the main flows are also indicated. The dryer can be divided into two main sections, an initial length (from the bricks entrance to the chimneys) and a second part from the chimneys up to the bricks exit section. In the first part, the initial water fraction is evaporated; in this area the main air flow is in co-current with the bricks. In the second portion of the dryer, the residual moisture is further evaporated with a main air flow in counter-current with the bricks. The necessary temperatures for the process are reached with a main burner in the second part of the dryer and 6 additional smaller burners located at four positions in the second part of the dryer and at two positions in the first part. The total average consumption of the dryers is 2.2 MW at average temperatures of about 200-260°C.

The actual bricks cooking process takes place in the central part of the kiln. The bricks, entering from the left side of , are first pre-heated, then cooked and finally cooled down before exiting the kiln. The air flows and the bricks are in countercurrent. A series of air vein burners are located along the cooking (where the maximum process temperature of about 900°C is achieved) and the pre-heating sections. The average thermal consumption is roughly 4.5 MW.

To optimize the energy use of the processes, a large heat recovery from the kiln is implemented, taking part of the hot air exiting the pre-heating section of the kiln and mixing it with the fresh air feed of the dryer at two different positions (dark blue lines in Fig. 1). This allows reducing the natural gas consumption to achieve the desired temperatures. Given the complexity of the internal air flows, and the difficulty of recirculating the tunnel kiln exhaust air (due to impurities), further air recovery interventions would not be feasible.

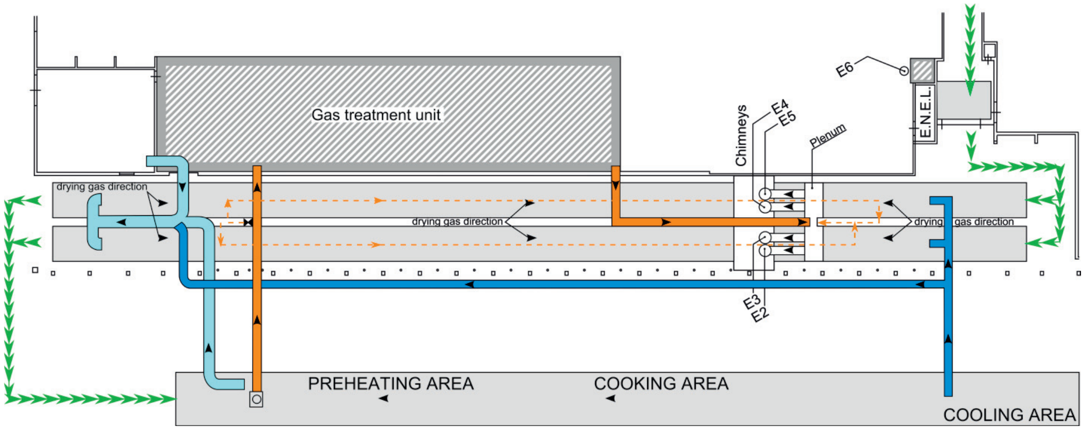

Fig. 1. Schematic layout of the bricks drying (top) and cooking (bottom) processes with bricks (green), outgas (orange) and air (light and dark blue) main flows.

2.2. Solar fields and heat integration

Solar heat is produced by Fresnel collectors with an overall area of about 2700 m^2 and a planned maximal capacity of 1.2 MW. The solar plant include two different fields, one with direct steam generation (DSG) and the second with thermal oil as hot thermal fluid (HTF) used for indirect steam generation by means of an oil-to-water steam generator. Through the implementation of the two steam generation technologies it will be possible to understand the strong points and the bottlenecks of both approaches and compare their performances at exactly the same boundary conditions.

The layout of the HTF field is shown in Fig. 2a, including the oil-to-water heat exchanger. Each block represents a series of collectors. For each collector series, the inlet and outlet temperatures are measured, while the mass flow is recorded for each circuit branch. Also the inlet and outlet temperatures to the solar field, the ambient temperature and the solar radiation are measured. Finally, the electrical consumption of the whole field (i.e. the oil pump and the additional auxiliary systems consumptions) is recorded.

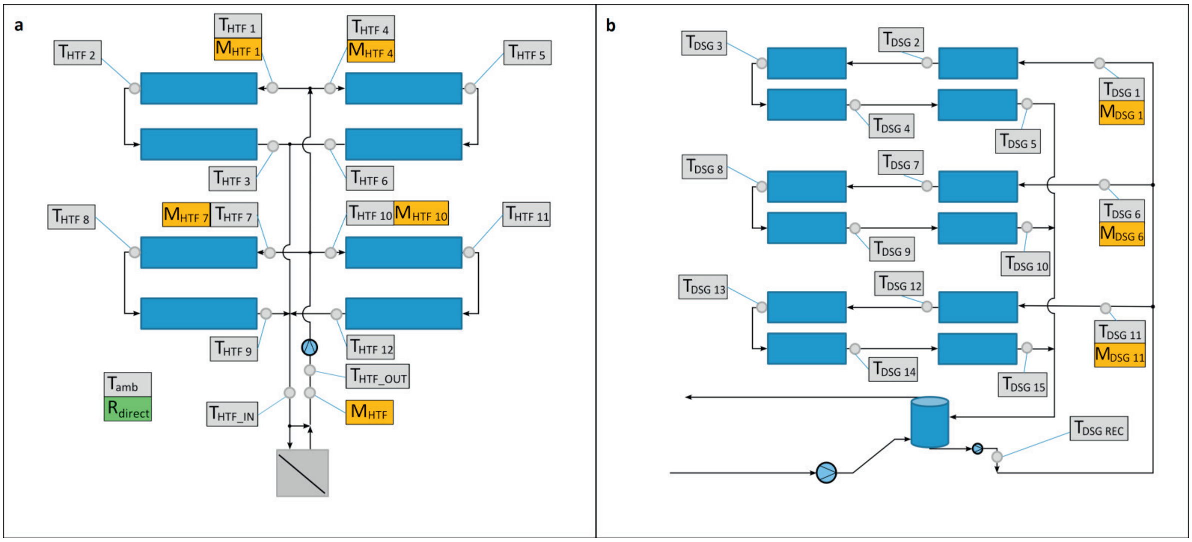

Fig. 2. (a) Layout of the HTF solar field; (b) layout of the DSG solar field.

The layout of the DSG field is showed in Fig. 2b. Temperature sensors are foreseen at the inlet and outlet of every collector series, while mass flow meters are installed only at the inlet of every circuit branch. However, since the fluid is in two-phase conditions, the recording of all the intermediate stages is not strictly useful to the monitoring. For these reasons, only the inlet values at every collector loop are saved, while the others signals are used only for online fault detection and the fine tuning of the control system. Another measurement point assesses the water temperature at outlet of the steam-drum. Again, the electric power consumption of the field is recorded, which include the two represented circulation pumps, besides all the auxiliaries.

Before being directed to the dryer, the steam from the two fields is merged at a temperature of about 180°C. In addition, a back-up natural gas burner connected in parallel with the solar fields, supplies steam in case of non-sufficient solar radiation. The integration of solar heat into the process is obtained with an air-to-steam radiant heat exchanger at the entrance of the dryer, as shown in Fig. 3.

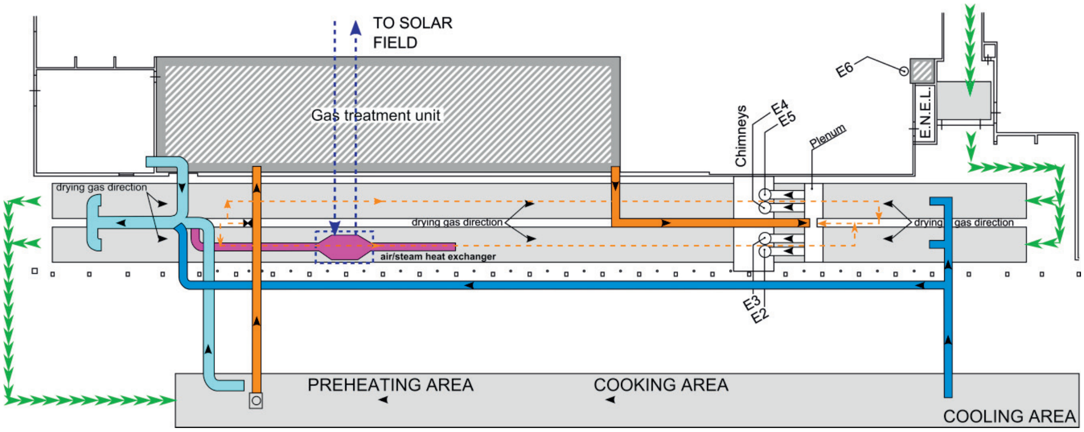

Fig. 3. Solar heat implementation in the dryer with an air-to-steam heat exchanger.

3. Monitoring procedure

3.1. Energy and data flow chart

To increase the combined process/solar-field control and the reliability of large scale solar thermal systems covering a high fraction of the process heat (>20%) a permanent and automated monitoring system is needed. For this purpose, the solar fields have been instrumented with temperature sensors and mass flow meters (see Fig. 2) allowing a deep understanding of the energy balances and response of the system to the control procedures adopted.

Additionally to this, a structured representation has been developed suitable to supervise the information recorded from a large number of data updating with time and to deliver integral performance parameters to the operators. This representation, based on the German guidelines for monitoring buildings and complex HVAC systems [2], is capable of describing both energy flows and meters signals. The energy flow chart representation (Fig. 4a), getting rid of the hydraulic illustration, allows easy energy flows analysis, energy balances and the overall performance characterization.

The scheme is divided into three sections: the Energy Supply level on top (different available energy sources are represented as horizontal lines), the Energy System in the middle (energy conversion systems and corresponding sensors are placed) and the Production Process at the bottom (final use of the converted energy). The 2 layouts represented in Fig. 2 are also represented separately in Fig. 4a (red boxes). Energy conversions and sensors are named accordingly to the specific field, while sensors with the label “INT” belong to the integration of the two solar fields, previously shown in Fig. 3.

In the signal flow chart representation (Fig. 4b), the same meters indicated in the energy flow representation are reported, while energy flows are not shown. The signal flow is represented as a line going from the sensor to the data logger and to the remote data storage. For this specific representation, the scheme is divided into two sections: data logging hardware and sensors.

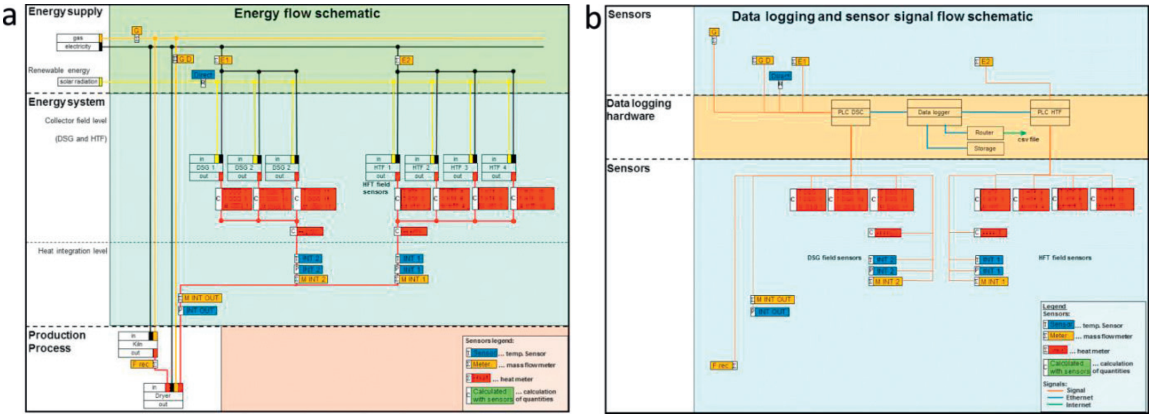

Fig. 4. Energy flow representation for the monitored plant; (b) Data logging and signal flow representation for the monitored plant.

4. Validation of the monitoring hardware

The first part of the solar collectors field (HTF) has been installed and commissioned in April 2013. The DSG portion is being installed at the time of this paper writing and will be commissioned before the end of 2013. The first phase of the monitoring phase has been used to validate the monitoring hardware and the basic temperature and mass flow measurements with respect to the HTF field. Until now, several days of data have been used for this purpose from July to September 2013. In the following, the measurements taken on the 6th of September 2013 have been selected as representative of the actual operation, during regular clear-sky conditions.

4.1. Validation of mass flow measurements:

In Fig. 5 the mass flows measured at the four collectors branches are reported. Since optimization is still undergoing aimed to define the most suitable oil flows for given radiation level, normalized values are reported here. As can be seen in chart (a), the mass flows show a regular operation: a two-step control of the system is used to maintain the temperature difference at the heat exchanger above 20 °C. Therefore, the mass flow is reduced when the sun radiation is not sufficient to run the plant at rated conditions.

Two distinct behaviors are noticed in terms of maximum mass flow obtained: the two collectors branches that lie closer to the heat exchanger experience an higher mass flow (see Fig. 2). Despite the effort during design, construction and commissioning phases -devoted to balance the flows through pipes of equal length and regulation valves- a small difference (in the range of 3%) could not be avoided up to now. In the next months, further actions will be undertaken to reduce the mismatch and a cost-to-benefit analysis will be elaborated by comparing consequences on installation costs and plant performance.

4.1. Validation of the temperature measurements

The inlet ($T_{HTF\_1, 4, 7, 10}$) and outlet temperatures ($T_{HTF\_3, 6, 9, 12}$) of each collectors branch are reported in Fig 6 and compared with the overall flow temperatures at the heat exchanger (see Fig. 2a, T_{HTF_in}, T_{HTF_out}).

Looking at the inlet temperatures (see Fig. 2a), it can be noticed a fluctuating behavior due to the plant operation: the collectors' loop drives a steam generator that operates in batch mode with cycles of about 10 minutes, and results in temperatures oscillations of about 1°C after the heat exchanger (i.e. oil side).

Again shifts can be noticed in the temperatures levels (see Fig. 2a): due to heat losses, a temperature drop of around 0.5°C is measured between the heat exchanger and the closest collectors branches. A further decrease (< 0.5°C) is noticed between the first and second branches. On the other hand, a good agreement between corresponding temperatures is observed. With respect to the outlet temperatures, two separate conditions are noticed as a consequence of the two mass flow levels encountered: the solar collectors experiencing the lowest mass flow undergo an higher temperature rise, by about 2°C. Investigations have been started to check and reduce the gap.

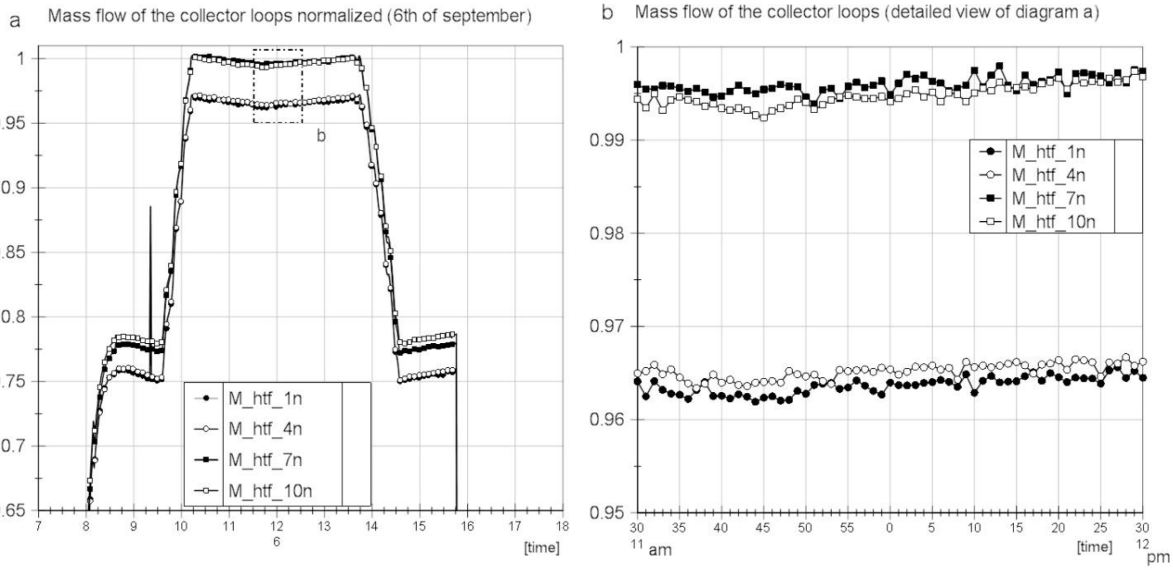

Fig. 5. (a) Mass flow of the collector loops; (b) Mass flow of the 4 collector loops and total mass flow.

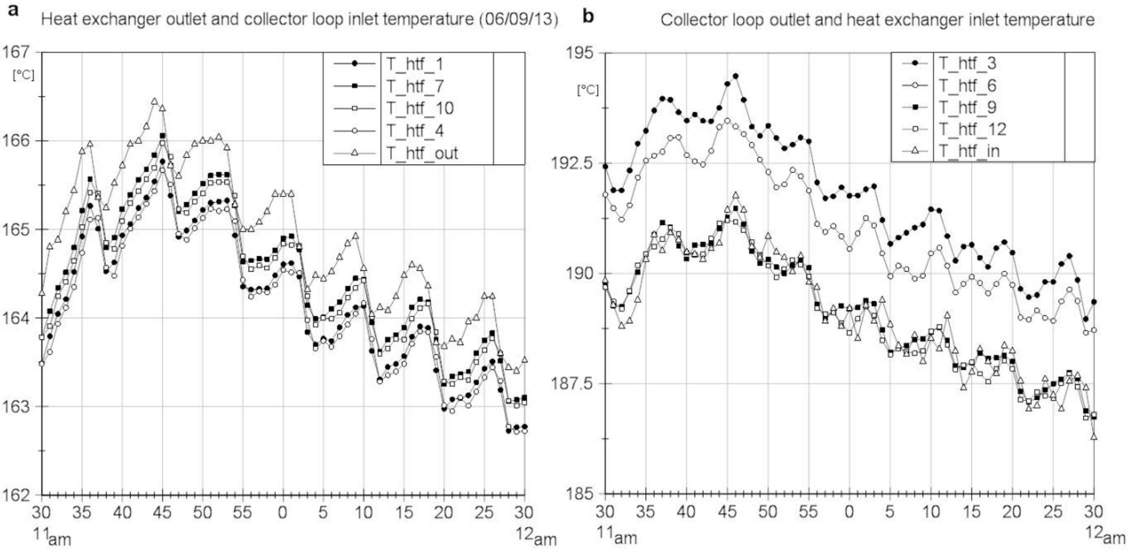

Fig. 6. (a) Collectors loop inlet temperatures and heat exchanger outlet; (b) Collectors loop outlet temperatures and heat exchanger inlet.

4.2. Instantaneous power assessment

In Fig. 7, the instantaneous thermal power is reported. The oil temperature fluctuations are passed to the power curves, however contributing by less than 5% to power average values A maximum peak power deviation in the range of 20% is noticed between the four branches: the lowest curve corresponds to the loop where the production and installation procedures have been tested the most. Looking at the three upper curves, it is seen how power output has been improved by 10% by using the commissioning procedure, and differences can be easily explained as a consequence of the small temperature and mass flow variations reported above.

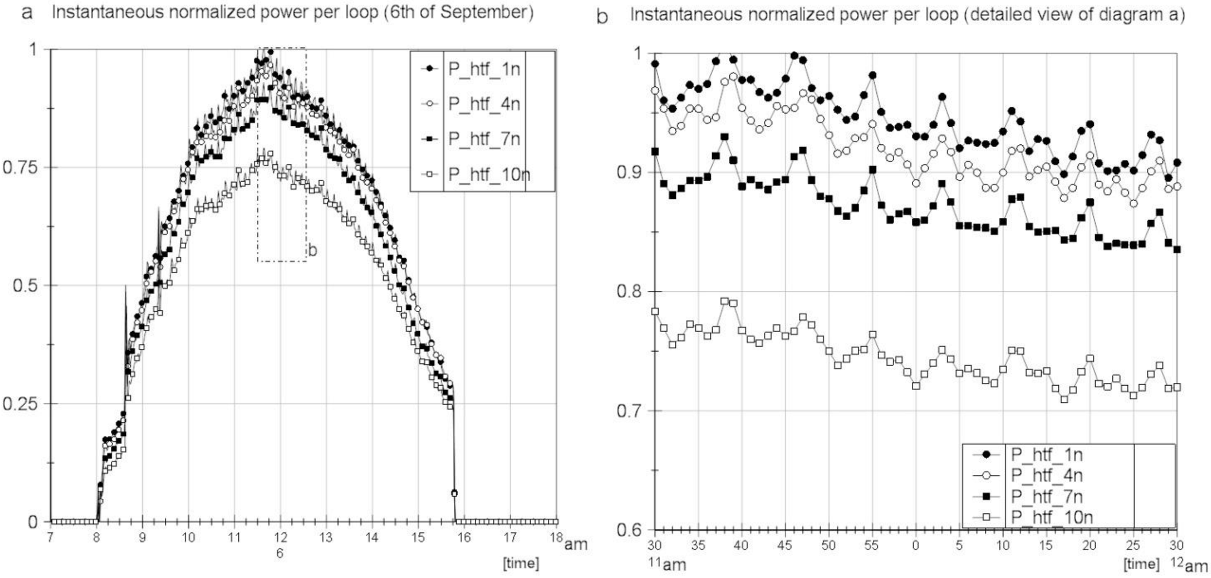

Fig. 7. (a) Instantaneous power in the four collector loops; (b) Total power and avg. power of the four collector loops.

5. Data reduction procedure

When a large amount of non-stationary monitoring data are collected, it is important to properly manage them from a statistical point of view, before performance figures are computed. As noticed in the previous section, the solar field performance are to some extent affected by fluctuations due, on the one hand, to the variations of the irradiation conditions and, on the other, to the steam generator batch operation. Although the fluctuations have in this case a limited extent (again a clear sky day was used to present data in Fig. 5 to Fig. 7), for a proper evaluation of the system performance -as it would be in a stationary test carried out in a laboratory under controlled conditions- a suitable data reduction procedure has to be used to get rid of the oscillations and assess the “average” performance.

The Bin Method Analysis (BMA) is being used in this project [3]-[4]. This technique consists in time-averaging instantaneous monitoring data, with the aim of reducing the influence of system operation. For the application investigated here, a period of 10 minutes has been considered to be the correct one to average the fluctuations due to the steam generator operation. The elaborated data are further averaged in bins to smooth the effects due to weather changes, and typical component performance curves are derived.

In the following, the evaluation of the efficiency curve of the single collectors is evaluated, as an explanatory example. Reduced temperature ($(T_m\text{-}T_{amb})/R_{dir}$) bins are generated, containing all the relative calculated efficiency data ($P_{th}/(A_{apert}*R_{dir}*IAM)$).

Fig. 8 shows the result of the analysis carried out with the first data available: the dataset is obtained by the superimposition of the instantaneous power calculations for the 8 collectors represented in Fig. 2a. As already stated, the plant is still facing an optimization phase, therefore again a normalized representation is reported. Moreover the amount of available data are is still not sufficient to be statistically representative.

The efficiency values in each bin are extremely uneven since, during transient operation, both irradiation and/or mass flows vary incoherently due to system inertia: instantaneously, efficiency values close to 1 or to 0 can be assessed. Therefore, the data in each bin are averaged and the resulting value is considered as the efficiency coupled with the average value of the bin. In general, it can be stated that the larger the number of data per bin, the more consistent the output from the analysis. For sake of consistency, each bin has to contain a number of data greater than 50.

The dataset consists of a large cloud of data varying mainly between 0.05 and 0.8 (hoverer values higher than 1 have not been disregarded within this analysis), and concentrated in a range of reduced temperature between 0.1 and 0.4 across the rated operating conditions.

Despite the mentioned limitations, a qualitative efficiency curve can be derived, summarizing the first operation performance. Interesting is the decreasing behavior at low values of reduced temperature (< 0.1): this would not be assessed during stationary tests since it is not due to collectors' malfunctioning; on the contrary it is related to whole system dynamics.

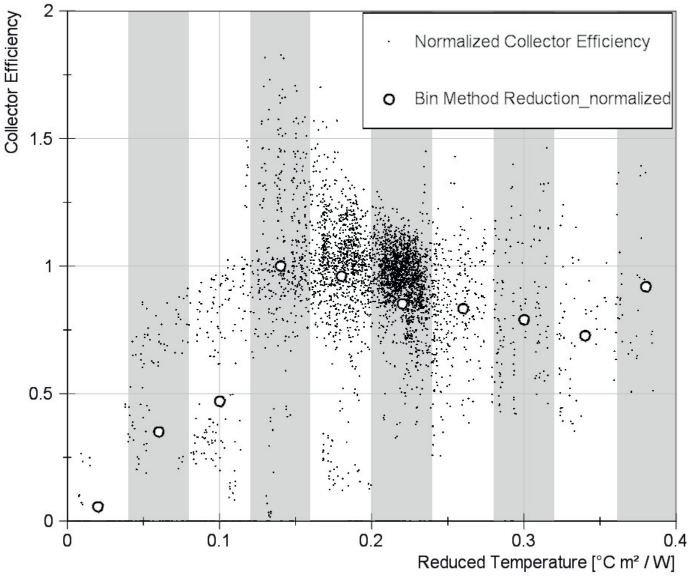

Fig. 8. Collectors efficiency curve normalized to the peak efficiency.

6. Conclusions

A large solar thermal field with a nominal capacity of 1.2 MW has been setup to provide thermal energy to the drying process of a brick company in the north of Italy. Two main loops have been installed warming thermal oil and directly producing steam. The first has been successfully commissioned in April 2013 and monitored since June 2013.

The monitoring data have been used to check and correct underperformance. Minor unbalances of the hydraulic circuits will be fixed in the near future. Despite the negligible weight on the mass flows distributions, this produces noticeable differences in terms of power outputs of the single collectors branches.

A statistical method (the Bin Method Analysis) is being adapted to the sector of the large solar thermal field. A first qualitative assessment has been reported with reference to the collectors efficiency characterization. A quantitative evaluation will be only possible when a data set sufficiently extended will be available. However, the analysis already provided preliminary indications with respect to the whole system dynamics. When quantitative information will be elaborated, this will allow validating the numerical models of the solar collectors, when used to simulate the entire solar thermal plant.

Acknowledgements

The research leading to these results has received funding from the European Union's Seventh Framework Programme FP7/2007-2013 under grant agreement n° ENER/FP7/296009/InSun

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