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(Article begins on next page)



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Installation of a concentrated solar power system for the thermal needs of buildings or industrial processes

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Abstract

Solar energy is one of the main alternatives to carbon-intensive sources of energy. However, limited attention has been devoted to small-scale (<10 kW) concentrated solar power systems, which are capable to provide high-temperature heat to buildings or industrial processes. In this work, we describe the concentrated solar power system (7.4 kW thermal power) with dual axis solar tracker installed at Politecnico di Torino. The solar concentrator system is coupled to a sensible heat storage by a plate heat exchanger. Here, we provide preliminary data on the system efficiency and compare it to typical values obtained by flat plates or evacuated tubes collectors. The generated high-temperature thermal power is suitable for both domestic hot water, heating and cooling, and industrial purposes.

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Keywords: Concentrated solar power; Solar dish; Thermal needs of buildings; Climate change mitigation; Cavity receiver; Sensible heat storage

1. Introduction

The recent agreement on climate change mitigation (COP21, Paris) imposes a progressive reduction of greenhouse gas emissions in the next decades. Fossil fuels currently provide approximately 85% of worldwide energy needs [1], therefore contributing to increase the concentration of carbon dioxide in the atmosphere and thus the global warming.

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In this context, the progressive adoption of renewable (and low-carbon) energy sources can play a fundamental role in reducing greenhouse gas emissions. However, technical and economic restraints are still limiting a wider and faster transition to renewable energy sources, mainly due to long return on investments, limited productivities and low energy densities. Solar energy is already one of the main alternatives to carbon-intensive sources of energy [2-4]. One of the most promising solar energy technology is Concentrated Solar Power (CSP), mainly because of thermal performances typically larger than flat plates or evacuated tubes collectors ones.

In this work, a parabolic solar dish concentrator with double-axis sun tracking mechanism recently installed at Politecnico di Torino is described and characterized. At design conditions (i.e. $I_N = 1000 \text{ W/m}^2$), the system can generate up to 7.4 kW thermal power (e.g. 120 l/h of water at 50°C).

The generated high-temperature thermal power is suitable for both domestic (e.g. hot water, heating and cooling) and industrial (e.g. desalination, enhanced oil recovery, steam generation) thermal energy needs, and it may lead to better return on investments and thus wider adoption of solar energy technologies.

Nomenclature

A_d	Net area of parabolic dish	m^2
A_r	Area of the cavity aperture	m^2
c_p	Specific heat capacity	$J/(kg \text{ K})$
C_r	Concentration ratio	-
f_L	Focal length	m
I_N	Direct Normal Irradiation (DNI)	W/m^2
L	Length of receiver	m
\dot{m}	Mass flow rate	kg/s
T_{in}	Inlet temperature	$^\circ\text{C}$
T_{out}	Outlet temperature	$^\circ\text{C}$
V	Capacity of the storage tank	l
$V_{ex,tank}$	Capacity of the expansion tank	l
$V_{f,l}$	Volume of the fluid in the primary circuit	l
Φ_d	Diameter of parabolic dish	m
Φ_{ri}	Diameter of cavity aperture	m
Φ_{re}	External diameter of receiver	m
η	Thermal efficiency of solar concentrator	-

2. Description of the experimental setup

CSP technologies are based on a reflecting optical element focusing the incident direct solar radiation onto a small receiving area. This generally leads to higher working temperatures and limited heat losses [4]. In case of parabolic solar receivers, a double axis tracking system is needed to follow the sun throughout its daily course, therefore increasing the amount of exploitable energy.

In Figs. 1 and 2, the solar concentrator installed at Politecnico di Torino (Turin, Italy) and considered in this work is depicted. The solar concentrator has been manufactured by Innova Energy Solutions (Turbocaldo). The structural components of the device are made of galvanized and stainless steel, while its overall weight is about 600 kg. The solar concentrator is coupled with a well-insulated sensible heat storage (water, $V = 1000 \text{ l}$) by means of a plate heat exchanger. Hence, the overall plant consists of a primary (from solar concentrator to plate heat exchanger) and a secondary (from plate heat exchanger to water tank) circuit, which both have pipes with 3/4" diameter.

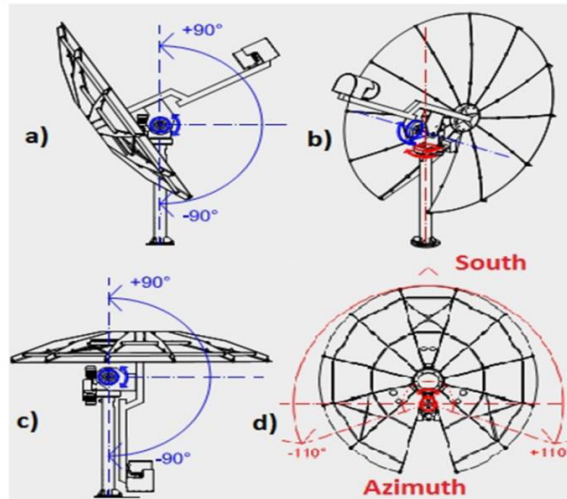


Fig. 1. Working position of the solar concentrator: (a) side view; (b) axonometric view. Safe position of the solar concentrator: (c) side view (d) top view.



Fig. 2. Picture of the solar concentrator installed at Politecnico di Torino (Turin, Italy). The receiver is depicted in the zoom inset.

2.1 Primary circuit

The primary loop is made of (i) hydraulic circuit, (ii) hydraulic/electric control units and (iii) solar concentrator. In Fig. 3, a schematic of the primary loop is depicted.

In the primary hydraulic circuit, a water-glycol mixture (60:40) flows from the cavity receiver of the solar concentrator, which is located on the rooftop, to the plate heat exchanger, which is located in a technical room. The distance between the parabolic solar dish and the heat exchanger is about 8 meters (see Fig. 3). Coherently with domestic applications (i.e. space heating and domestic hot water), the circuit is designed to work with fluid temperatures up to 110°C. However, the circuit can be easily modified to operate with diathermic oil, therefore achieving temperatures suitable for industrial applications (up to 250°C). The mass flow rate in the primary circuit lies in the range 7-19 l/min.

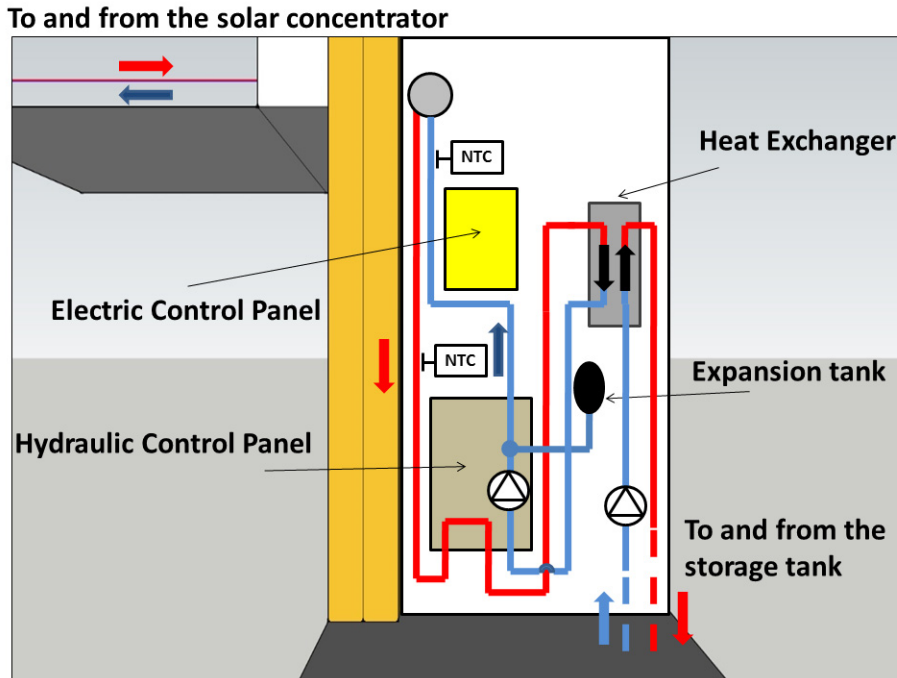


Fig. 3. Scheme of the primary circuit. The technical room is represented by white background.

The primary loop also includes a hydraulic control unit, which contains a turbine type flow meter (Huba Control DN15) and two thermocouples (NTC – Negative Temperature Coefficient – sensors in Fig. 3) measuring the inlet (T_{in}) and outlet (T_{out}) temperatures to/from the solar collector. These thermocouples allow monitoring the instantaneous production of thermal energy. An electric control unit (sun tracking control), an expansion tank ($V_{ex,tank} = 25 \text{ l}$), a pump (Grundfos solar 25-65 130 mm), an automatic filling unit (pressure control of the heat carrier fluid) and four automatic vent valves (air bubbles evacuation from the heat carrier fluid) are also present in the primary loop. The automatic vent valves are installed at the highest point of the hydraulic circuit. The volume of the expansion tank is evaluated using the following sizing equation:

$$V_{ex,tank} = 0.1815 \cdot V_{f,l} + 14.3 \quad (1)$$

where $V_{f,l}$ is the volume (in liters) of the heat transfer fluid in the primary circuit (water-glycol mixture).

The parabolic dish of the solar concentrator is made out of 11 highly reflective multilaminar aluminum foils (89% optical efficiency, Almirr Alucoil®), which guarantee excellent structural balance and low stress on sun tracking motors and gears. The optical efficiency is an average value over the solar spectrum; however, the trend is fairly constant across the entire spectrum of solar radiation wavelengths, due to the multilayering nature of foils. The diameter of the parabolic dish (\varnothing_d) is equal to 3.75 m, while the mirror surface has an effective area (A_d) of 9.58 m² to collect the direct solar radiation (DNI) and concentrate it into a metallic black-cavity receiver, which is coated by black selective coating to enhance its absorptance. The focal length (f_L) is set to 2.26 m, in order to achieving the optical convergence within the inner volume of the cavity receiver. The system is equipped with rain and wind sensors, so that the solar concentrator automatically goes into safe position in case of heavy rains or wind speeds beyond 50 km/h.

The solar cavity receiver is made of stainless steel and it acts as heat exchanger (see Fig. 4). The concentrated solar radiation enters the cavity through an aperture with $\varnothing_{ri} = 0.18 \text{ m}$ diameter (see the heat absorbing surface in Fig. 4), which corresponds to $A_r = 255 \text{ cm}^2$ area. Therefore, the geometric concentration ratio ($C_r = A_d/A_r$) is almost 400. The heat carrier fluid flows within a pipe coil in direct contact with the internal surface of the black-cavity, in order to

harvest the absorbed solar energy. As reported in Fig. 4, a layer of thermal insulating material (rockwool) is placed between the pipe coil and the outermost surface of the solar cavity receiver, in order to reduce thermal losses. The external diameter of the receiver (Φ_{re}) is equal to 0.37 m, while its length (L) is 0.57 m. This cavity receiver configuration is adopted to maximize the net absorption of concentrated radiation [4, 5]. Indeed, high temperatures are achieved by concentrating solar energy on a relatively small area and, at the same time, heat losses are drastically reduced due to the limited heat exchange surface with ambient.

2.2 Secondary circuit

The secondary loop (11.2 m of pipes, which are thermally insulated by a polyethylene foam coating) allows coupling the solar collector with the sensible heat storage, by means of a plate heat exchanger. The latter has an exchange area equal to 0.45 m² and it is characterized by a global heat transfer coefficient equal to 3548 W/m²K. The sensible heat storage consists of a well-insulated water tank, which can contain up to 1000 liters of domestic hot water. A NTC thermistor (10 Ohm) communicates the maximum water temperature in the tank to the electric control unit, in order to control the pumps of both primary and secondary circuits. On the one side, the solar concentrator is defocused in case water temperature exceeds a safe threshold (i.e. T_{boiler} equal to 90°C). On the other side, when no thermal power is generated by the solar concentrator, the pump of primary circuit is switched off, while two electric boilers (1.5 kW and 80 liters each) can automatically replace the solar concentrator in the production of domestic hot water (and vice versa). Currently, the electric boilers are activated by a simple on/off strategy, but a more efficient and automatic control system is under development.

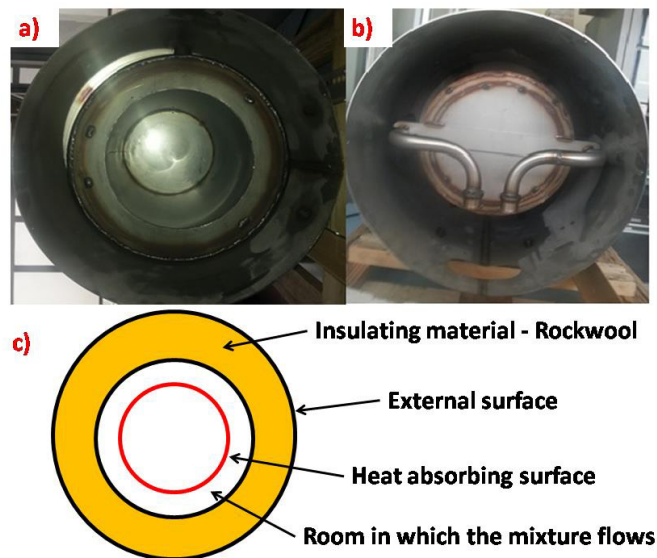


Fig. 4. Pictures of the solar cavity receiver: a) front view; b) back view; c) section schematics.

3. Results

In this section, preliminary data from the considered CSP system are reported and discussed. The experimental data were collected on December 1, 2015. The conversion efficiency (Eq. 2) is defined as the power absorbed by the heat carrier fluid in the primary circuit divided by the direct component of solar irradiation (I_N) on the solar dish surface (A_d), namely

$$\eta = \frac{\dot{m} c_p (T_{out} - T_{in})}{I_N A_d}, \quad (2)$$

where \dot{m} is the mass flow rate of fluid. I_N is obtained from PVGIS database [6], whereas the specific heat capacity of heat carrier fluid (c_p) is evaluated by a mixing rule for the water-glycol mixture (60:40), at proper working temperatures. In the considered working hours, the mass flow rate has almost constant values (i.e. 9.2 l/min).

In Fig. 5, the direct component of the solar radiation is depicted (1st December 2015, Turin). The meteorological conditions of the day chosen for the experimental measures allow to safely assuming clear sky conditions in the 11:50-15:30 time interval. In Fig. 6, η is plotted from 11:50 to 15:30, where the performance of the system is almost constant and equilibrium conditions are achieved. In fact, a relatively limited difference between the average temperature of the heat carrier fluid in the primary circuit and ambient air is observed during the experiments, which leads to similar heat losses in the primary and secondary loops. Note that measures in a wider time interval would also involve a transient analysis of the system, which is currently in progress.

These preliminary results show that the average conversion efficiency is close to 65%, with peaks up to 78%. In agreement with previous studies in the literature, the installed CSP system shows thermal performances higher than the ones typically achieved by traditional flat plate or evacuated tube collectors [7]. In Fig. 7, the temperature increase in the water tank is also reported, namely a 15°C rise from 11:50 to 15:30.

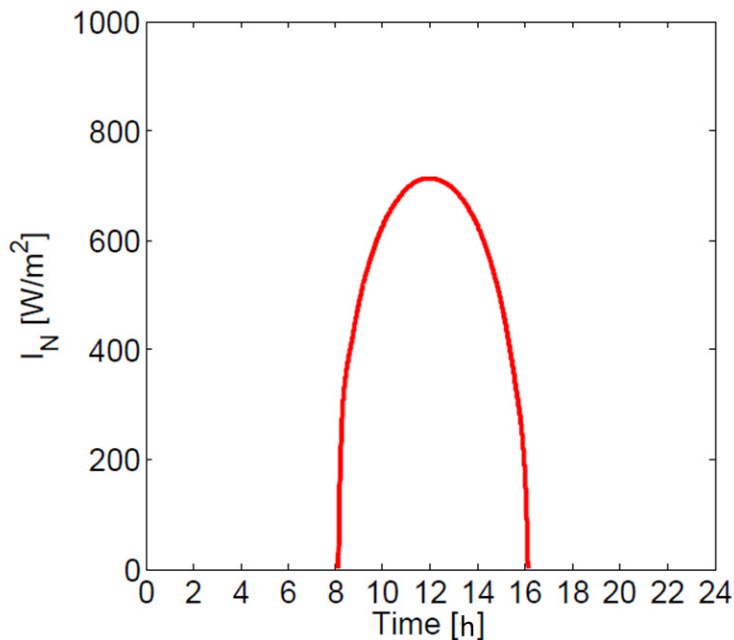


Fig. 5. Direct Normal Irradiation (DNI). Measures refer to clear sky conditions (1st December 2015, Turin).

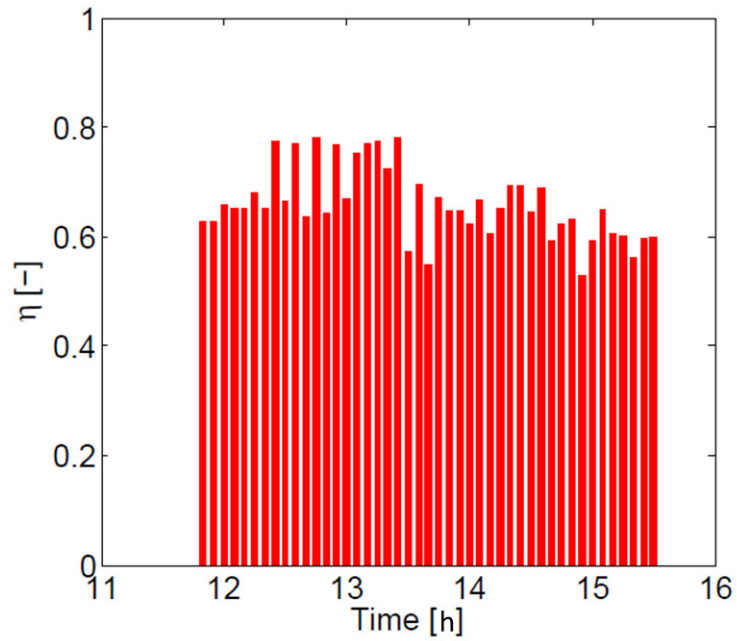


Fig. 6. Thermal efficiency of the CSP system. Measures refer to clear sky conditions (1st December 2015, Turin).

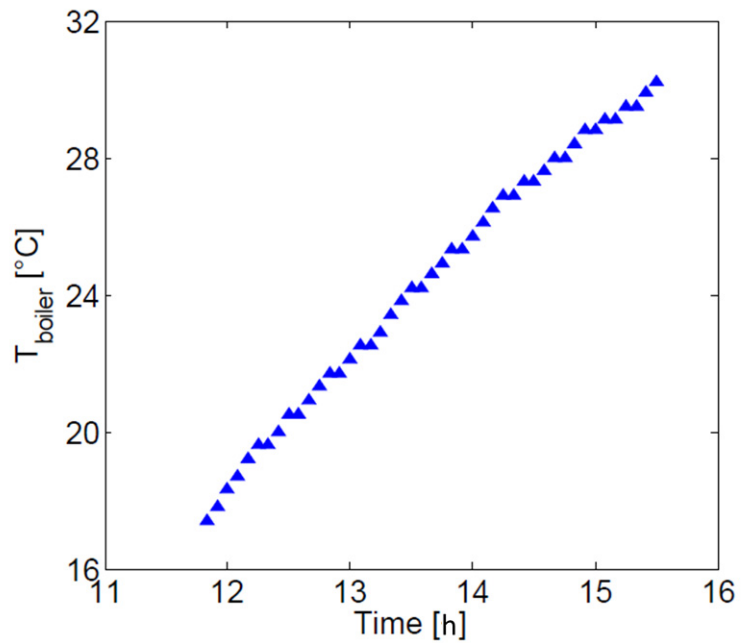


Fig. 7. Temperature of water (1000 l) in the heat storage tank. Measures refer to clear sky conditions (1st December 2015, Turin).

4. Conclusions and perspectives

In the recent years, the scientific interest in renewable sources of energy is increasing, because of their important contribution to reduce climate change. However, the transition from fossil to solar energy requires the optimization of collection, storage and transport processes [5, 8].

In this work, a small-scale (i.e. <10 kW) concentrated solar system for thermal power generation is described. Thanks to a reflecting parabolic surface, direct solar radiation is focused with precision in the black cavity of a compact solar receiver. The reduced heat exchange surface with the ambient leads to limited thermal losses and thus high solar absorption efficiencies [4]. The solar concentrator is then coupled with a sensible heat storage (water tank) by means of primary and secondary hydraulic circuits, which are interfaced by a plate heat exchanger. Preliminary results show that the conversion efficiency of the system, namely the ratio between the sensible heat absorbed by primary circuit and the incident solar radiation, shows average values close to 65%.

In perspective, the crucial elements to further enhance the overall thermal performance of small-scale CSP systems and thus fill the gap between lab-scale and industrial-scale applications are the solar cavity receiver and the heat storage device. On the one side, a possible innovative way to improve the solar-to-heat conversion efficiency is the use of volumetric solar receivers based on solar nanofluids, which are characterized by large optical absorption coefficients [9, 10]. On the other side, heat storage devices are fundamental to smooth the mismatch between sun availability and user needs. In particular, the adoption of heat storage systems based on adsorption processes (e.g. zeolites [11, 12]) could lead to both longer (loss-free) accumulation times and higher storable energy at fixed storage volume.

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